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16. ABSTRACT

This report provides the details of an evaluation of the distribution and biological impacts of particulate materials in combined sewer and storm drain discharges in the Seattle, Washington region, and presents the extent of the urban runoff problem in terms of statistics and observed and anticipated impacts on water quality in Lake Washington and Puget Sound. The potential public health risk related to enteric viruses associated with such particulates is also addressed.

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*Particulates	Hydrocarbons	Oil and grease	
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Virus			
*Storm sewers			

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August 1980

FATE AND EFFECTS OF PARTICULATES DISCHARGED BY COMBINED SEWERS AND STORM DRAINS

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FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report provides the details of an evaluation of the distribution and biological impacts of particulate materials in combined sewer and storm drain discharges in the Seattle, Washington region, and presents the extent of the urban runoff problem in terms of statistics and observed and anticipated impacts on water quality.

Francis T. Mayo, Director
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PREFACE

The quality of semi-natural waters in urban areas is directly related to the amount of local human activity. Efforts to protect urban waters for recreational uses require a knowledge of discharge sources of pollution, pollutant loadings and the effects of these pollutants on the receiving water, the benthic communities and the public health of the local populace.

The Municipality of Metropolitan Seattle Water Quality Laboratory contributes to this knowledge through environmental programs designed to:

1) monitor surface waters within King County for biological and chemical parameters,

2) assess the effects of stormwater runoff and treatment plant discharges on water quality,

3) monitor recreational waters and shellfish for microorganisms of sanitary significance, and

4) investigate the impacts of industrial waste discharges on water quality.

This report details an investigation of the fate and ecological effects of particulates in stormwater runoff and combined sewer discharges entering Lake Washington and Puget Sound. The potential public health risk related to enteric viruses associated with such particulates is also addressed.

ABSTRACT

The distribution and biological impacts of discharged particulates were evaluated for selected combined sewer outfalls (CSOs) and storm drains (SDs) in the Seattle, Washington region. Intensive studies were done on one CSO and one SD discharging into Lake Washington and having residential drainage basins of comparable size and incident rainfall. The mean storm discharge concentrations of suspended solids and most particulate contaminants were greater for the CSO than for the SD. However, due to the SD's greater discharge volume (runoff + baseflow), its annual particulate discharge load was greater for Cu, Pb, organic carbon and chlorinated hydrocarbons. Human enteric viruses were also detected in the CSO discharge, but were not found in storm drainage or in any near-outfall sediments. Prevailing circulation patterns implied a negative sanitary impact of CSO discharges on adjacent recreational areas.

Light transmission measurements of discharge plumes identified extensive additional inputs from neighboring CSOs, SDs and construction sites. Particulate distributions were influenced by various dispersion processes, including water density layering, near-bottom offshore streaming and longshore advection.

Oligochaete numbers and biomass were found to be substantially enhanced near two CSOs and two SDs studied in Lake Washington. Near-outfall depletion of other taxons at both CSOs and SDs also provided evidence of effluent toxicity and/or substrate alterations. Impacts of discharges on the freshwater benthos raised concern relative to the feeding success of sportfish.

Discharge concentrations of selected contaminants were also assessed for a marine CSO. On the basis of six different biological indicators sensitive to water and sediment quality, the nearshore area within 150 m of that outfall was characterized as polluted.

This report was submitted in fulfillment of Grant No. R805602010 by the Municipality of Metropolitan Seattle under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from October 27, 1977 to October 23, 1979, and work was completed as of July 31, 1979.

CONTENTS

Page

- Foreword iii
- Preface iv
- Abstract v
- Figures ix
- Tables xiv
- Abbreviations and Symbols xvii
- Acknowledgement xviii

- 1. Introduction 1
    - Project origins 1
    - Project objectives 5
- 2. Summary and Conclusions 7
    - Freshwater studies 7
    - Marine studies 11
- 3. Recommendations 13
- 4. Method of Study 15
    - Selection of sampling sites 15
        - Preliminary freshwater studies 15
        - Intensive freshwater studies 17
        - Marine studies 17
    - Description of sampling sites 17
        - Preliminary freshwater studies 17
        - Intensive freshwater studies 17
        - Marine studies 18
    - Field sampling methods 21
        - Combined sewer and storm drain discharges 21
        - Settling particulates 23
        - Sediments 25
        - Benthic biota 26
        - Viruses 28
    - Analytical techniques 29
        - Combined sewer and storm drain discharges 29
        - Settling particulates 30
        - Sediments 31
        - Benthic biota 32
        - Viruses 34
    - Data reduction 36
        - Combined sewer and storm drain discharges 36
        - Settling particulates and sediments 37
        - Benthic biota 37

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CONTENTS

Page
5. Results 40
    Freshwater studies 40
        Preliminary studies 40
        Intensive studies 45
    Marine studies 99
        Discharge monitoring. 99
        Turbidity distributions of discharge plumes 101
        Sediment particle size distributions. . . . 108
        Benthic biota 111
6. Discussion. 133
    Effects of discharges on littoral food chains. . 133
        Freshwater environment. 133
        Marine environment. 137
    Extrapolation of present findings to other outfall sites. 139
    Extent of nearshore waters affected by discharge particulates 140
        Freshwater environment. 140
        Marine environment. 141
    Distribution and effects of discharge-borne viruses. 142

References. 145
Appendix. 154
Glossary. 159

FIGURES

Number Page

1 Locations of major water bodies and sewage treatment plants in the Seattle area. 2

2 Locations of sampling sites 16

3 Principal set of intensive sampling sites in Lake Washington 19

4 Secondary set of intensive sampling sites in Lake Washington 20

5 Details of sampling transects around the Denny Way Regulator Outfall, 1978 22

6 Details of sediment trap configuration. 24

7 Configurations of the sediment trap arrays moored at the principal sampling sites in Lake Washington. . 25

8 Relative enrichment of the nearshore surface sediments of Lake Washington with normalized categories of parameters. 41

9 Summary of rainfall and overflow response at Combined Sewer Outfall 023 and Storm Drain 7 from March 1978 to February 1979. 52

10 Aerial perspectives of contours of percent light transmission at Combined Sewer Outfall 023-- 1533-1645 hrs., 3/7/78. 57

11 Longitudinal sections of contours of percent light transmission at Combined Sewer Outfall 023-- 1533-1645 hrs., 3/7/78. 58

12 Longitudinal section through the Combined Sewer 023 outfall, showing contours of percent light transmission--0856-0954 hrs., 4/4/78. 59

FIGURES

Number Page

13 Aerial perspectives of contours of percent light transmission at Combined Sewer Outfall 023--1330-2330 hrs., 2/6/79. 60

14 Transverse section through a point 34 m S of Combined Sewer Outfall 023, showing contours of percent light transmission--1330-2330 hrs., 2/6/79. . 61

15 Aerial perspectives of contours of percent light transmission at Storm Drain 7--1915-2014 hrs., 2/6/78. 62

16 Aerial perspectives of contours of percent light transmission at Storm Drain 7--2244-2348 hrs., 2/6/79. 63

17 Transverse sections through a point 61 m N of Storm Drain 7, showing contours of percent light transmission on 2/6/79 64

18 Transverse section through a point 344 m N of Combined Sewer Outfall 023, showing contours of percent light transmission--2244-2348 hrs., 2/6/79. . 65

19 Aerial perspectives of contours of percent light transmission at Control Site 3--0506-0549 hrs., 2/12/79 66

20 Transverse sections showing contours of percent light transmission at Control Site 3--0506-0549 hrs., 2/12/79 67

21 Aerial perspectives of contours of percent light transmission at Combined Sewer Outfall 044--2210-2350 hrs., 2/11/79 68

22 Aerial perspectives of contours of percent light transmission at Storm Drain 19--0020-0250 hrs., 2/12/79 69

FIGURES

Number Page

23 Summary of results of particle size distribution analyses for Combined Sewer Outfall 023 and Storm Drain 7 75

24 Dry weight distributions of lead, zinc, copper and total carbon in the surface centimeter of sediments collected near Combined Sewer Outfall 023 . . . 78

25 Dry weight distributions of lead, zinc, copper and total carbon in the surface centimeter of sediments collected near Storm Drain 7. 79

26 Dry weight distributions of lead, zinc, copper and total carbon in the surface centimeter of sediments collected at Control Site 3 80

27 Net change in numbers of organisms and biomass per core, as a function of distance from the combined sewer and storm drain outfalls in February and September, 1978 93

28 Summary of rainfall and overflow response at the Denny Way Regulator outfall from March 1978 to February 1979 102

29 Aerial perspectives of contours of percent light transmission around the overflow outfall of the Denny Way Regulator--0517-0746 hrs., 4/16/78. 104

30 Aerial perspectives of contours of percent light transmission around the overflow outfall of the Denny Way Regulator--2050-2243 hrs., 2/24/79. 106

31 Transverse sections of contours of percent light transmission around the overflow outfall of the Denny Way Regulator--2050-2243 hrs., 2/24/79. 109

32 Summary of particle size distribution analyses for the Denny Way Regulator 110

FIGURES

Number Page

33 Variation in the condition indices of mussels and oysters kept in pots at four sites near the Denny Way Regulator outfall during 1978 112

34 Size data for Enteromorpha collected near the Denny Way Regulator outfall during April and August, 1978 . 115

35 Density of infaunal individuals and taxa found in the subtidal samples collected near the Denny Way Regulator outfall during April and August, 1978 118

36 Species-richness curves for molluscs collected near the Denny Way Regulator outfall during April and August, 1978. 120

37 Species-richness curves for polychaetes collected near the Denny Way Regulator outfall during April and August, 1978. 121

38 Dendrogram of subtidal infauna samples collected near the Denny Way Regulator outfall during April and August, 1978. 122

39 Positions of subgroups of sites from cluster analysis of samples of subtidal infauna collected near the Denny Way Regulator outfall during April and August, 1978. 123

40 Proportions of the total number of annelids, arthropods and molluscs collected near the Denny Way Regulator outfall during April and August, 1978 .125

41 Proportions of total numbers of polychaetes within each of three feeding-type categories, for samples collected near the Denny Way Regulator outfall during April and August, 1978 127

42 Species-richness curves for periphyton samples collected near the Denny Way Regulator outfall during April 1978. .128

FIGURES

Number Page

43 Position on canonical variables of periphyton samples collected near the Denny Way Regulator outfall during April 1978. 128

44 Species-richness curves for macroalgae collected near the Denny Way Regulator outfall during April and August, 1978. 130

45 Position on canonical variables of samples of boulder wall taxa collected near the Denny Way Regulator outfall, 1978 131

TABLES

Number Page

1 Correlation Matrix for CSO Sediments 44

2 Correlation Matrix for Storm Drain Sediments 44

3 Correlation Matrix for Control Sediments 44

4 Summary of Rainstorms Monitored for Quantity and Quality of Discharges into Lake Washington 45

5 Summary of Estimated Total Pollutant Loads and Fraction of Particulates in Storm Discharges Monitored at Combined Sewer Outfall 023 and Storm Drain 7. 47

6 Interstation Comparison for Storm Drain 7 and Combined Sewer Outfall 023 of Mean Discharge Concentrations and Pollutant Loadings. 48

7 Summary of Virus Analyses of Discharges from Combined Sewer Outfall 023 and Storm Drain 7 50

8 Estimated Total Annual Masses of Selected Constituents in Discharges from Combined Sewer Outfall 023 and Storm Drain 7. 53

9 Summary of Field Trips for Measuring Turbidity Distributions of Discharge Plumes. 55

10 Correlation Coefficients for Nearshore Sedimentation Rates vs. Volume of Discharge from Combined Sewer Outfall 023 and Storm Drain 7. 70

11 Summary of Results of Two-Way Analysis of Variance for Sediment Trap Collections from Combined Sewer Outfall 023, Storm Drain 7 and Control Site 3. . . . 71

12 Mean Sedimentation Rates and Dry Weight Concentrations of Selected Constituents Analyzed in Sediment Trap Solids Collected at Combined Sewer Outfall 023, Storm Drain 7 and Control Site 3 71

TABLES

Number Page

13 Summary of Virus Analyses of Receiving Waters near Combined Sewer Outfall 023 and Storm Drain 7 74

14 Significant Differences Between Mean Station Concentrations for Selected Parameters Analyzed in the Top 0.5 Centimeter of Sediment Cores Collected at Combined Sewer Outfall 023, Storm Drain 7 and Control Site 3 77

15 Mean Concentrations and Concentration Ratios for Selected Metals in Particulates Sampled at Combined Sewer Outfall 023, Storm Drain 7 and Control Site 3 81

16 Upper Confidence Limits Expressed as Percentages of the Means for 2, 4, 6, 8 and 10 Cores per Sampling Location for Chironomid, Oligochaete and Copepod Counts 85

17 Coefficients of Determination for Linear and Multiple Regressions Using Total Organism Counts in February as the Dependent Variable 89

18 Coefficients of Determination for Linear and Multiple Regressions Using Total Organism Counts in September as the Dependent Variable. . . . 90

19 Coefficients of Determination for Linear and Multiple Regressions Using Total Organism Weight in February as the Dependent Variable 91

20 Coefficients of Determination for Linear and Multiple Regressions Using Total Organism Weight in September as the Dependent Variable. . . . 92

21 Summary of Rainstorms Monitored for Quantity and Quality of Discharges into Puget Sound from the Denny Way Regulator Outfall 99

22 Statistical Summary of Estimated Pollutant Loads and Concentrations in Storm Discharges Monitored at the Denny Way Regulator 100

TABLES

Number Page

23 Estimated Mass of Selected Constituents in Discharges from the Denny Way Regulator Outfall 101

24 Rainfall, Overflow Volumes and Tidal Variations for Overflow Turbidity Distributions Monitored Around the Denny Way Regulator Outfall. 103

25 Tissue Burden of Heavy Metals in Mussels Kept in Pots at Four Sites near the Denny Way Regulator Outfall 114

26 Tissue Burden of Heavy Metals in Oysters Kept in Pots at Four Sites near the Denny Way Regulator Outfall 114

27 Characteristics of Subtidal Sediments Sampled near the Denny Way Regulator. 116

28 Characteristics and Annelid Densities of Intertidal Soft Sediments Sampled near the Denny Way Regulator 129

LIST OF ABBREVIATIONS AND SYMBOLS

α	volume attenuation coefficient
Al	aluminum
BGM	Buffalo Green Monkey cells (for virus analysis)
C	carbon
ClHC	chlorinated hydrocarbons
CI	Condition Index (for shellfish)
CSO	combined sewer outfall
Cu	Copper
g	grams
Hg	Mercury
H_2S	hydrogen sulfide
kg	kilograms
km	kilometers
m	meters
mE	meters east of line through outfall
MG	million gallons
mg	milligrams
MLLW	mean low low water
mN	meters north of line through outfall
mS	meters south of line through outfall
mW	meters west of line through outfall
NA	not applicable
ND	not determined
O&G	oils and greases
P	phosphorus
Pb	lead
PCB	polychlorinated biphenyls
ppb	parts per billion
ppm	parts per million
r	correlation coefficient
σ, S_x	standard deviation
SD	storm drain
TOC	total organic carbon
TPO_4-P	total phosphate phosphorus
$\bar{X}$	arithmetic mean
Zn	zinc

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SECTION 1

INTRODUCTION

PROJECT ORIGINS AND RESEARCH FOUNDATION

The City of Seattle is surrounded by a multiplicity of both natural and modified water bodies (Figure 1). It is bounded on the west by the central basin of Puget Sound, part of a great complex of channels and inlets having a maximum depth of 267 m just three kilometers northwest of West Point. To the east of the city lies Lake Washington, which extends 29 km on a north-south axis. Although the natural outlet for the lake was originally at its southern end, the flow patterns were altered in the early 1900s with the construction of a canal and saltwater locks between Lake Washington and Puget Sound; this waterway became the principal outlet for Lake Washington and provided a navigable link through Lake Union to Puget Sound. Seattle makes heavy commercial and recreational use of both this east-west canal and its primary north-south watercourse, the Duwamish River, whose estuary on Elliott Bay hosts extensive saltwater port facilities.

Seattle's concern for the maintenance of good quality for its bounty of waters led to the formation in 1958 of the Municipality of Metropolitan Seattle (Metro), a public corporation vested with the responsibility for areawide sewage disposal. Previously, both treated wastes and raw sewage had been discharged to fresh and marine waters throughout the region. Metro, however, consolidated the facilities of some 30 agencies and provided for treatment and discharge of all sanitary wastes at four treatment plants (POTWs) on Puget Sound and one on the Duwamish River (Figure 1). This approach served to eliminate most of the visible impacts of haphazard waste discharge - most notably, the dense algal blooms consistently appearing in Lake Washington. But the peak flow volumes associated with rain storms are too great for even the revised treatment system to accommodate and combined sewer overflows continue to occur throughout the city under such conditions. The assessment and abatement of any consequent environmental impacts has been given high priority by Metro as part of its responsibility for maintaining good regional water quality.

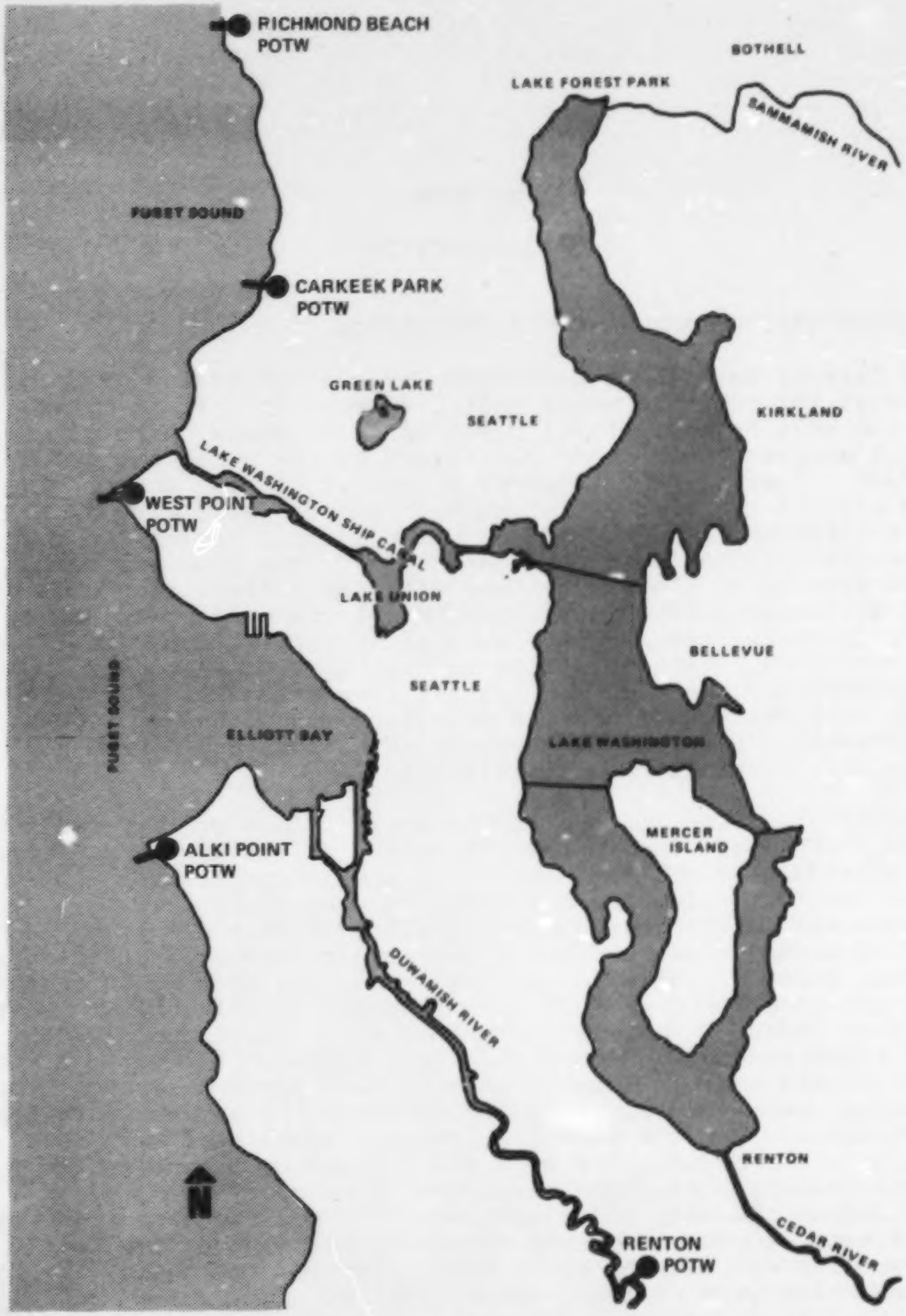
RICHMOND BEACH POTW
BOTHELL
LAKE FOREST PARK
SAMMAMISH RIVER
PUGET SOUND
CARKEEK PARK POTW
GREEN LAKE
SEATTLE
KIRKLAND
LAKE WASHINGTON SHIP CANAL
WEST POINT POTW
LAKE UNION
BELLEVUE
SEATTLE
PUGET SOUND
ELLIOTT BAY
LAKE WASHINGTON
MERCER ISLAND
ALKI POINT POTW
DUWAMISH RIVER
RENTON
CEDAR RIVER
RENTON POTW
N

Figure 1. Locations of major water bodies and sewage treatment plants in the Seattle area.

The extent of the present combined sewer overflow problem in Seattle can be explained in terms of statistics, locations and observed and anticipated impacts on water quality. Statistically speaking, there are about 160 overflow locations in the Seattle area, of which 30 are under the jurisdiction of Metro and the remainder are the responsibility of the City of Seattle. A brief, intense rainstorm can gorge city collector sewers, causing basement backups and discharges to Lake Washington. In contrast, a milder storm of longer duration will tend to flow more smoothly to the larger trunk sewers where a buildup of flow beyond treatment and interceptor trunk capacity will lead to programmed overflows to the lower Duwamish River, Elliott Bay and Lake Union. These longer storms, typical of the winter season, may result in less than 50 percent of municipal wastewater actually reaching the West Point Treatment Plant during the actual storm period. Operation of Metro's Computer Augmented Treatment and Disposal (CATAD) System, which provides in-line storage in some of the larger sewers, permits some flexibility as to discharge location, with highest priority given to protection of freshwater bodies (Lake Washington, Lake Union) where possible. Frequency of overflow at present is estimated to average about 40 occurrences per outfall per year, of which perhaps five or six are summer occurrences.

Geographically, combined sewer and storm drain outfalls are scattered throughout the area, with discharges of varying volumes to all of the major water bodies around the City of Seattle. Some of these discharges are over shellfish beds, or as in Lake Washington, near public bathing beaches or spawning areas for anadromous fish; others are in the harbor area where water contact sports or potential public health hazards are minimal.

In wet weather, sewer flows comprise varying mixtures of street and rooftop drainage, infiltration/inflow and raw sewage. This untreated wastewater can be generally characterized as a dilute sewage with typical BOD values of 100 to 200 mg/l. Suspended solids values also vary widely: 50-525 mg/l for combined wastewaster (Metro, 1976) and 54-112 mg/l for storm runoff (Farris et al., 1974) (Metro data show 36-96 mg/l and 2-24 mg/l respectively for primary and secondary treatment plant effluent).

Studies done by Dalseg and Leiser (1970) of the quality of wastewater entering Lake Washington from two combined sewer overflows and two storm drains yielded solids concentrations five to ten times higher for the combined wastewater than for the storm drainage. However, physical separation of one of the combined systems had resulted in an estimated fivefold annual increase of suspended solids discharge at that location due to the increased number of storm drain overflows.

Further calculations indicated that each inch of rainfall resulted in 1330 lb of suspended solids loading from one of the storm outfalls; the comparable figure for one of the combined outfalls was 650 lb. The Seattle area has an annual average rainfall of about 100 cm.

During August of 1976 Metro's Water Quality Division monitored four combined sewer outfalls in the Seattle region. The results of the study (Tomlinson et al., 1976) indicated potential problems from discharged particulates and their associated toxins. First-flush suspended solids concentrations at three of the stations reached levels exceeding 500 mg/l. In addition, deposits of black, oily sediments were found at the ends of three lake and river outfalls. The highest concentrations of heavy metals were found at or near the outfalls. High concentrations of pesticides (up to 1.95 ppm dry wt.) were also found in the sediments near the single outfall monitored in Lake Washington.

It appears that much of the particulate fraction of wastewater overflows may be deposited near the outfalls. Summer season dye studies indicate that the nearshore surface circulation at two lake stations is comparatively sluggish, providing a maximum dilution of 2.7:1 (Lake Washington) and 75:1 (Lake Union) during the first three hours following release. Such conditions might be expected to favor the near-shore settling of much of the sediment injected into the environment by combined sewer outfalls and storm drains.

Very little information is available concerning the effects of combined sewer overflows and storm drainage on freshwater benthic communities. White (1975) has discussed the potential influence of fluctuations in organic particulates on the community distributions of many of the benthic organisms; population increases of these organisms were generally related to increases of organic material. On the other hand, alterations in particle size distributions and toxicity increases in the community substrate as a result of urban runoff might be expected to be detrimental to such populations. The importance of many of these taxonomic assemblages as primary or secondary elements of the freshwater food chain has been documented by Tomlinson et al. (1977).

Further, there is a strong need for information relative to the effects of discharged particulates and their associated contaminants on the benthic biota around marine sewer outfalls and storm drains. Armstrong et al. (1978) conducted a preliminary investigation on the effects of discharges from one of Metro's principal marine CSOs on the adjacent hard- and soft-bottom benthic biota; based on their analyses, they were able to delineate a zone of impact attributable to the CSO. These marine investigations were limited to the Spring, however, and the authors expressed the need for correlative work to be done during other seasons to assess any differences due to variations in discharge characteristics. Additional studies would need to consider the impacts of the seasonality of discharges on seasonal biological processes.

Beyond the concern for aquatic biota, there is considerable apprehension on the part of public health workers over the presence of infectious viruses in CSOs. A large portion of these pathogens has been shown to be associated with the particulate fraction (Lund, 1973; Wellings et al., 1976). All of the major groups of viruses known to be present in sewage are extremely stable and can be transmitted by the fecal-oral or the respiratory route. Investigations carried out by Metro have yielded estimates of 3.2×10^2 infectious virus units per liter of raw influent sewage at the West Point Treatment Plant (Swartz et al., 1978). Thus, CSOs in or near areas utilized for water contact recreation pose a potential risk to the health of recreationists.

With the recent advent of quantitative virus detection techniques, it has become apparent that the concentrations of viruses of human origin in sewage usually vary seasonally, reaching a peak during the late Summer and early Fall. This variation reflects the higher infection rates that occur during the warmer months of the year (Grabow, 1968). Given their extensive qualitative potential for human infection (Fenner and White, 1976) a quantification of the viruses released into the nearshore recreational environment is a needed step toward a determination of public health protection measures.

Therefore, in view of their potential impact on the health of both the endemic aquatic biota and human recreationists, there is an urgent need for more data on the loading, distribution and effects of combined sewer and storm drain particulates and their associated contaminants entering Seattle's nearshore waters. The present project was designed to provide this type of information.

PROJECT OBJECTIVES

The principal project objectives were as follows:

1. To determine the distribution patterns and fate of suspended particulates emanating from representative combined sewer outfalls and storm drains in the Seattle area. To determine seasonal differences and to correlate quantitative in-situ observations with suspended solids loading factors and current patterns.

2. To determine the effects of the settled particulates and associated contaminants on the population distributions of benthic organisms.

3. To determine concentrations of viruses in CSO discharges and their concentrations and persistence in fresh receiving waters and near-outfall sediments.

4. To determine the distribution patterns and ultimate fate of selected particulate discharge contaminants, including copper, lead, zinc, carbon and phosphorus.

SECTION 2

SUMMARY AND CONCLUSIONS

FRESHWATER STUDIES

A preliminary study of sediments near 29 combined sewer outfalls (CSOs), storm drains (SDs) and control sites in Lake Washington provided the following observations, which served as a guide for the selection of the principal (intensive) study sites:

1) A composite enrichment index (including metals, pesticides, PCBs, organic carbon, total phosphorus and oils and greases) indicated that the southwestern portion of the lake had the most highly contaminated nearshore sediments. These pollutants were from combined sewers and storm drains serving the City of Seattle. Several stations along this shore had a composite sediment enrichment of more than 16 times background levels. The sediments at the northern end of Mercer Island were also found to be highly contaminated.

2) The measured pesticide content of the sediments was predominantly DDT and its degradation products. Contamination levels of pesticides along the Seattle shoreline of Lake Washington were up to 37 times background concentrations. Pesticides were present in the sediments around both CSOs and SDs and gave evidence of being associated predominantly with storm water in both types of systems.

Intensive studies of contaminant loading, discharge plume circulation, the characteristics of settling particulates, and sediment contaminant distributions were carried out all or in part at 2 CSOs, 2 SDs and 2 control sites, with the following conclusions:

1) Discharge plume distributions were studied only in the absence of thermal stratification of the lake. At all study sites, including one CSO, one SD and one control, major secondary inputs were detected and identified as construction runoff or discharges from neighboring CSOs and SDs. The discharge plumes from the study outfalls rose through the water column and formed surface lenses

of turbid water covering up to 10.1 hectares while still intact as a definable entity. A fraction of the discharged particulates remained thus for as much as a day or more following an overflow, (depending on local circulation dynamics); another portion was found to quickly settle around each outfall and then move offshore along the bottom.

2) Circulation patterns at some of the study sites were defined as unexpectedly complex. Turbid storm drainage was observed entering a control site via longshore advection.

3) The representative CSO and SD sites had significantly higher mean sedimentation rates than did the control area, by an average factor of 2.9 times. Data from a related study indicate that sedimentation rates just offshore from the outfalls are 2.5 times the control values, reflecting the near-bottom offshore movement of discharge particulates. The total flux (input per unit area) to the control sediments of all particulate contaminants was determined to be significantly lower than for the CSO or the SD.

4) Sediment and discharge particle size distributions were determined for the representative CSO and SD. The median particle size for the discharge particulates was appreciably smaller for the SD than for the CSO, indicating a higher potential for transport away from the outfall. There was evidence that the turbulence caused by the discharges washes the finer particulates away from the outfall area at both sites. There were indications of the breakdown of particulates and the dissipation of organics near the outfalls during dry periods.

5) The general trends observed with respect to wastewater impacts on the benthic infauna near 2 CSOs and 2 SDs implied enhancement of oligochaetes(aquatic earthworms) at all sites, with the greatest enrichment of the worm communities occurring at the CSO locations. This difference between site types was assumed to be due to the fact that much of the particulate matter in the CSO discharges had been predigested in human guts, making the carbon more readily available to microorganisms, which are in turn the principal food of oligochaetes. On the other hand, there was also evidence of near-outfall depletion of chironomids (aquatic insect larvae) at three of the four study locations, implying toxic effects and/or impacts of substrate alterations. For chironomids, there were indications that a permanent zone of depletion (coinciding with an area of visible discharge

debris) existed around the outfalls; populations within these areas remained depressed the year around, whereas those farther away varied inversely with the seasonal rate of discharge. The impacts on the populations of copepods (microcrustaceans) and nematodes (roundworms) were more variable and less extreme; these organisms were negatively affected in most instances. The statistical analysis of the pelecypod (freshwater mussel) population indicated only slight and varied reactions to the presence of the CSO or SD discharge.

6) Using regression analyses of infaunal biomass as a function of distance from an outfall, estimates were derived for biomass increase or decrease due to CSO and SD discharges. The impacted area around a representative CSO was determined to be 0.6 hectares (1.4 acres). The total mean oligochaete biomass determined for two control areas of similar size and depth was 57.9 kg (127 lb) fresh weight. The impacted outfall area had an estimated additional biomass (enrichment) of 47.3 kg (104 lb) of oligochaetes. It was further estimated that this weight of prey organisms implied a potential increase of about 5 kg, or 10 lb of consumer organisms (fish) per year. Oligochaetes constituted over 90% of the total infaunal biomass at this station, and the described discharge impact was the most extreme one observed. The effects of consumption of tainted organisms by fish were not assessed. Also it was acknowledged that potential negative effects of the discharges on fish reproduction, not measured for this project, constitute a pollutional influence of unknown, and possibly serious magnitude.

7) Human viruses were readily detected in the CSO discharges. None were found in storm drainage. The level of viruses in a given sample of combined discharge was linked to time of day as related to the cyclic use of local restroom facilities.

8) No human viruses were found in receiving water samples collected near the SD. During an overflow at the CSO, however, viruses were detected at a level representing an estimated end-of-pipe dilution of 32:1. No viruses were found near the CSO 24 hours after the overflow. It was concluded that combined sewer overflows may constitute a health hazard for people using Lake Washington beaches soon after overflows, as in the summer months. This conclusion was based on literature indicating that viruses present at detectable levels can cause infection.

9) For a total of 42 separate samples collected near the CSO and SD outfalls soon after overflows, no viruses were detected in the top 3 cm of the bottom sediments.

10) The fraction of storms resulting in overflows was determined to be approximately 76% for the one CSO and the one SD monitored, with 48 overflows at each site during the one year study period, for which the total incident rainfall was 59 cm. The total overflow volumes for the two systems during the one year period were quite similar, being 25,600 m^3 (6.76 MG) for the CSO and 27,700 m^3 (7.32 MG) for the SD. The non-storm base flow (near-surface soil "interflow" plus groundwater infiltration) at the SD added another 50,200 m^3 (13.3 MG) to its total discharge.

11) For one CSO and one SD with similar size drainage basins (120-acre average), land-use types (residential), and rainfall, the mean storm overflow concentrations for many of the measured parameters (including suspended solids, copper, zinc, total phosphorus, oils and greases and selected chlorinated hydrocarbons) were lower at the SD than at the CSO. This was true for both the particulate and total (i.e. particulate + soluble) contaminants. Lead concentrations were much higher at the SD. However, because CSO flows are intermittent by nature whereas those from storm drains are continuous, the mean pollutant load discharged by the SD during a given storm period was typically similar to that from the CSO for all parameters except lead, total phosphorus and oils and greases. The storm loading for Pb was generally much higher at the SD, whereas the total mass discharge for TPO_4-P and O&G was lower.

12) The total mass of solids discharged by the principal CSO and SD monitored during the one year study period was approximately three metric tons each, with 20 percent of the SD solids being contributed by non-storm base flow. Of the particulate fraction, the respective annual mass loadings from the CSO and the SD were 10.7 kg and 5.2 kg of phosphate-phosphorus, 5.2 kg and 10.3 kg of heavy metals and 1.3 g and 1.2 g of pesticides.

13) Contaminant distributions for the surface layer of the bottom sediments around the representative CSO and SD outfalls (representing residential land use) indicated localized enrichment, with apparent modifications from current action and near-bottom downslope streaming. The concentrations of metals in the sediments were generally only 20-50% of those measured for settling particulates, implying selective removal of the contaminated particulates to deeper areas. Statistical analysis of the relative surface sediment distributions for copper, lead and zinc indicated different transport characteristics for each metal due to their association with particulates of different sizes and/or weights. Sediment enrichment with lead, zinc and copper, respectively, was determined to

average 9 times, 2 times and 3 times near the outfalls and 7 times, 2 times and none at the control site.

MARINE STUDIES

The conclusions for investigations carried out at and near Metro's Denny Way Regulator, a computer-controlled combined sewer overflow facility, were as follows:

1) Determination of the discharge plume distributions was complicated by a 1.5-3.0 m (5-10 ft) thick surface layer of highly turbid water from the Duwamish River moving past the Denny Way facility. However, the river water was generally excluded from the nearshore area just north of the outfall by the CSO plume. Following one or more complete tidal cycles, the CSO plume assumed a more symmetrical distribution around the outfall. The area measurably impacted by settling particulates extended 200-300 m along the shore in both directions from the outfall.

2) Compared to the particulates emitted by the study outfalls in Lake Washington, the solids discharged at Denny Way had a much higher organic content and smaller median size. The surface sediments near the outfall showed evidence of heavy inputs of CSO particulates. As opposed to the drainage basins of the CSO and SD studied in Lake Washington, which are less than 5% commercial/industrial, over one third of the Denny Way drainage area is commercial/industrial. The total area of the marine system is more than 5 times that of either of the freshwater basins.

3) With respect to substantial impacts on the local aquatic biota, the nearshore area within 150 m of the Denny Way outfall can be referred to as polluted. This was confirmed by a sampling regime used to quantify six different biological parameters known to be sensitive indicators of water and sediment quality. The relative effects were evident at the 9 m depth contour, but somewhat diminished farther (approximately 100 m) offshore at 13 m depth. There was some evidence that during periods of few overflows the shallow subtidal infauna does undergo a small degree of recovery toward more natural conditions. The results of the biological studies correlate well with previous work done at the same site.

4) The fraction of total storms resulting in overflows at Denny Way was 51% for the study year, the total number of overflows being 36. The total overflow volume was 6.60 X $10^5 m^3$ (175 MG) for an annual total rainfall of 99 cm. The associated mass of suspended solids emitted by the

outfall during this period was 85.1 metric tons. Of this particulate fraction, 7.6 metric tons was organic carbon, approximately 0.4 metric ton was heavy metals, and less than one gram was pesticides.

5) Compared to the combined sewer and storm drain discharges monitored in Lake Washington, the mean concentrations of heavy metals in both the particulates and the particulate + soluble wastes discharged at Denny Way were higher, reflecting the large component of industrial and commercial inputs to the latter system. However, its mean concentration of particulate chlorinated hydrocarbons was much lower, implicating residential use as the principal source of pesticides.

SECTION 3

RECOMMENDATIONS

Further work is needed to relate the localized findings of this project to Lake Washington as a system. It is suggested that mesoscale studies be conducted that cover at least one extended nearshore section (perhaps 2 km long) substantially inundated by CSOs only, and likewise one affected by storm drainage only; such areas have been identified in the lake. Toxicant distributions in these areas (including those for the EPA organic priority pollutants, which have recently been found in substantial concentrations in local freshwater and marine sediments) could be defined from analysis of sediment grid samples and related to detailed biotic community distributions determined by numerical classification analysis. One major advantage of mesoscale studies is the statistical elimination of the variability associated with single drainage systems.

The virus data described herein constitute a good foundation, but survival measurements and more detailed nearshore circulation studies would permit public exposure estimates as an adjunct to epidemiology measurements presently underway.* Virus measurements also should be made in marine waters in locations such as the Denny Way Regulator, which adjoins a public park having some water contact recreation. In addition, our failure to locate viable viruses in the near-outfall sediments presents a major conflict with work done elsewhere (Gerba et al., 1977); the reasons for this apparent contradiction need to be resolved.

Although the present work provided estimates of wastewater impacts on standing crop numbers and biomass for infaunal communities, it was noted that reproduction and toxicant tissue burden information on fish constitute very important deficiencies in our knowledge of the biological impacts on higher organisms.

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*The Municipality of Metropolitan Seattle is presently (1979-1980) involved in an epidemiology study in conjunction with EPA and the University of Washington that is designed to identify relationships between disease incidence in swimmers and levels of indicator bacteria. The determination of a good indicator organism would permit local authorities to set meaningful standards for the safe use of recreational waters.

It is suggested that investigations of this sort be done in Lake Washington using the prickly sculpin, an important primary carnivore and principal food item for many of the larger fish species. This fish exhibits only limited migration tendencies and might be expected to remain within impacted or non-impacted areas for the duration of such a study. A commercially-harvested crayfish species also abounds in the lake and could be investigated for effects of CSO and SD wastewater discharges.

Light transmission measurements were shown to be useful indications of general circulation trends. Their utility might be extended through correlations with grab sample analyses of various particulate pollutants, comparisons that would provide further information relative to the differential particle sorting patterns and solids dispersion characteristic of each species. Light transmission measurements are also needed as indicators of wastewater circulation patterns under stratified conditions in the lake.

Near-bottom time series of light transmission data would help to clarify the velocity and dimensions of turbidity plumes streaming offshore from an outfall. Sectioned cores collected along an onshore-offshore transect identified by this approach would provide age-dated profiles of pollutants to further our knowledge of particulate deposition rates and patterns.

Finally, it is suggested that study plans be made to take advantage of overflow abatement work imminent in Lake Washington. Construction will begin soon on a new pumping system downstream of the CSO 023 outfall, the principal freshwater combined sewer outfall investigated for the present project. The effect will be that overflows will cease entirely at CSO 023 in about two years. The opportunity to study the response of the environment to this alleviation of pollutant stress is rare and should be turned to good account.

SECTION 4

METHOD OF STUDY

SELECTION OF SAMPLING SITES

Preliminary Freshwater Studies

Prior to the present study, no comprehensive map was available giving the locations and dimensions of the sewer outfalls in Lake Washington. On the lake's western shore the Seattle sewer system and outfalls represent a composite of ancient and modern facilities that have grown with the city since its founding in 1851. Overall, the documentation for these structures is extensive. However, much of the eastern shore was settled in the last two decades; all of the sewers there are separated, and the details of storm drain facilities (including locations) had not been comprehensively plotted.

Drawing information from a number of sources, as much of the available outfall information as feasible was compiled to provide a comprehensive choice of study sites. A base map was constructed using sub-basin drainage charts (RIBCO, 1974).

Further details were obtained through visits to the files of pertinent agencies representing the nine sewer districts surrounding the lake. The resultant map (Figure 2) included 23 emergency outfalls (activated only by power failures), 34 CSOs, 56 pump stations and 240 SDs. For Lake Washington's 115 km of shoreline, this gave a conservative average of three outfalls per km. The map, although not complete, was felt to include all of the major drainage systems.

Using the compiled information, candidate sampling sites (13 CSOs, 20 SDs and 15 control locations) for the preliminary study were selected. In this, we were guided by two principal criteria: 1) that the locations be as free as possible of contamination from other outfalls, and 2) that the selected facilities have a high probability of large and frequent storm overflows or direct drainage responses.

Outfall interferences were judged from map information. Data on estimated (modelled) overflow frequency, volume and duration for each of the CSOs were obtained from the City of Seattle

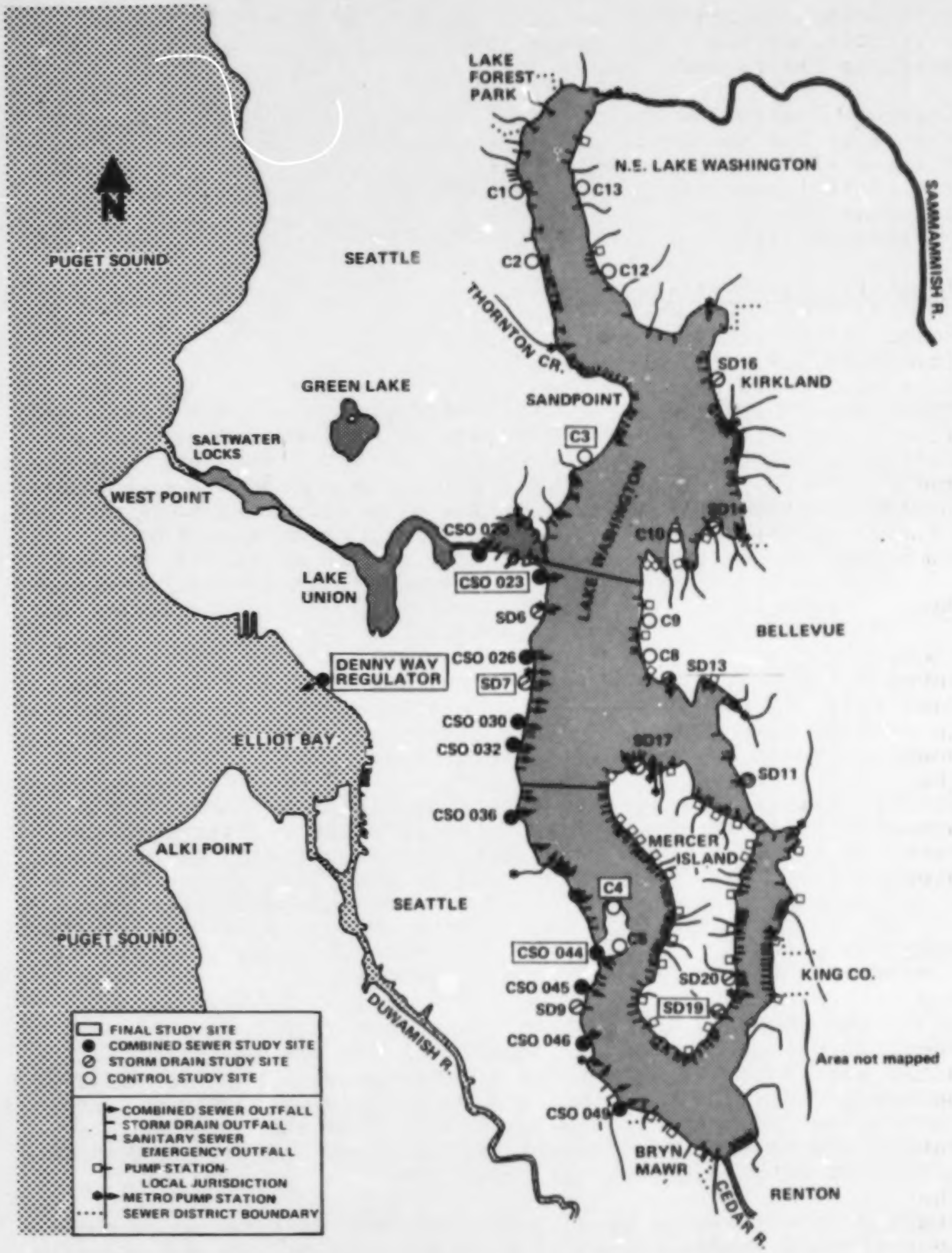

N
LAKE FOREST PARK
N.E. LAKE WASHINGTON
SAMMAMISH R.
C1
C13
PUGET SOUND
SEATTLE
C2
C12
THORNTON CR.
SD16
KIRKLAND
GREEN LAKE
SANDPOINT
C3
SALTWATER LOCKS
WEST POINT
LAKE WASHINGTON
SD14
CSO 02
C10
CSO 023
LAKE UNION
SD6
C9
BELLEVUE
CSO 026
C8
SD13
DENNY WAY REGULATOR
SD7
CSO 030
ELLIOT BAY
SD17
CSO 032
SD11
CSO 036
ALKI POINT
MERCER ISLAND
C4
SEATTLE
PUGET SOUND
CSO 044
C5
CSO 045
SD20
KING CO.
SD9
SD19
DUWAMISH R.
CSO 046
Area not mapped
CSO 049
BRYN/MAWR
CEDAR R.
RENTON
FINAL STUDY SITE
COMBINED SEWER STUDY SITE
STORM DRAIN STUDY SITE
CONTROL STUDY SITE
COMBINED SEWER OUTFALL
STORM DRAIN OUTFALL
SANITARY SEWER EMERGENCY OUTFALL
PUMP STATION LOCAL JURISDICTION
METRO PUMP STATION
SEWER DISTRICT BOUNDARY

Figure 2. Locations of sampling sites.

Engineering Department; because similar information was unavailable for the SDs, those facilities having the largest drainage basins were chosen.

Further on-site inspection resulted in elimination of some of the sites due to uncharted interferences or predicted difficulties with equipment installation, servicing and protection. The remaining stations were rated on the basis of the various concerns noted, and ten in each category were chosen for the preliminary field studies (Figure 2).

Intensive Freshwater Studies

Based on the results of the preliminary survey, six stations (two CSOs, two SDs, two control sites) were selected for intensive study. To this end, two additional criteria were added to those previously mentioned: 1) that the CSOs and SDs have strong localized indications of contamination by wastewater effluent, and 2) that the control areas be geographically close and physically similar to the relative CSOs and SDs. The locations of the final six stations (CSOs 023 and 044, SDs 7 and 19 and Controls 3 and 4) are shown in Figure 2 with their code numbers enclosed in rectangular boxes.

Marine Studies

The marine studies were carried out at one of the largest (in terms of both size and discharge volume) combined sewer overflow facilities in the Seattle area. The Denny Way Regulator Station is a computer-controlled CSO that discharges mixtures of raw sewage and street runoff into Elliott Bay on Puget Sound (Figure 2). This facility was selected for study on the basis of its size, frequency of overflow (average of 38/year), accessibility, and its location in the midst of a large public park, which extends 350 m to the south and 1100 m to the north along the shore of the bay.

DESCRIPTION OF SAMPLING SITES

Preliminary Freshwater Studies

The descriptions given below for the intensive freshwater study sites may be considered generally representative of conditions observed at the 14 additional preliminary sites.

Intensive Freshwater Studies

The locations ultimately chosen for the intensive freshwater studies (Figure 2) were the best available but did not fully meet all of our specified criteria. For any of the four outfalls selected, there was a substantial potential for discharge interference from other, nearby systems. This is particularly evident in Figures 3 and 4, which show the site configurations for the two CSOs. In each case, a large storm drain was found within several hundred feet of the combined sewer outfall. However, the approximate dimensions of the zone of debris accumulation observed by the divers indicated that the separation distances were probably sufficient to minimize interferences; also, probable current patterns deduced from dye studies in the general vicinity of these two locations (CH2M/Hill, 1974) indicated that the discharge plumes were likely to be parallel in most instances and not convergent.

The two combined sewer outfalls were found to have scoured pits at the ends, with built-up piles of debris somewhat further offshore. The pits were approximately half a meter deep and one meter wide; the mounds were as much as 1.5 m high and 14 m across (somewhat smaller at CSO 044 than at CSO 023). The discharge points for the two storm drain systems were nearshore (SD 7) or onshore (SD 19) in localized riprap, and opened onto much steeper terrain than did those of the CSOs, thus minimizing scouring and debris buildup.

Evidence of scouring and deposition was found to be common at the many outfalls investigated for the preliminary studies; at each such location, the sediment samples were taken just past the crest, on the back side of the debris mound. Active outfall structures were also found to have transient contiguous areas of visible debris accumulation, as large as 0.6 hectare (1.4 acres), as indicated in Figures 3 and 4. The dimensions of the biological sampling arrays, the locations of the sediment traps and the transmissometer grid configurations are also shown in these diagrams. The pipe diameter for all four outfalls was 61 cm. The typical substrate for the various areas was: CSO 023 - fine sand, silt, light debris; CSO 044 - pebbles, sand, silt, clay, light debris; SDs 7 and 19 - fine sand, silt, some clay, light debris; C 3 - sand; C 4 - sand, some silt, light debris.

The service areas associated with the four outfalls were: CSO 023 - 47.3 hectares, CSO 044 - 67.2 hectares, SD 7 - 50.6 hectares, SD 19 - 42.9 hectares. The CSO 044 sewers were partly separated, with street drainage being discharged to the lake through a nearby storm drain (Figure 4); rooftop drainage was discharged through the combined system.

Marine Studies

The marine studies were carried out around Metro's Denny Way Regulator CSO, where discharged materials enter the receiving waters through a conduit located in the intertidal zone. The sampling program was conducted in the intertidal and shallow subtidal (down to 13 m below MLLW, Mean Lower Low Water) regions in an area bounded by Pier 70 to the south and Pier 91 to the

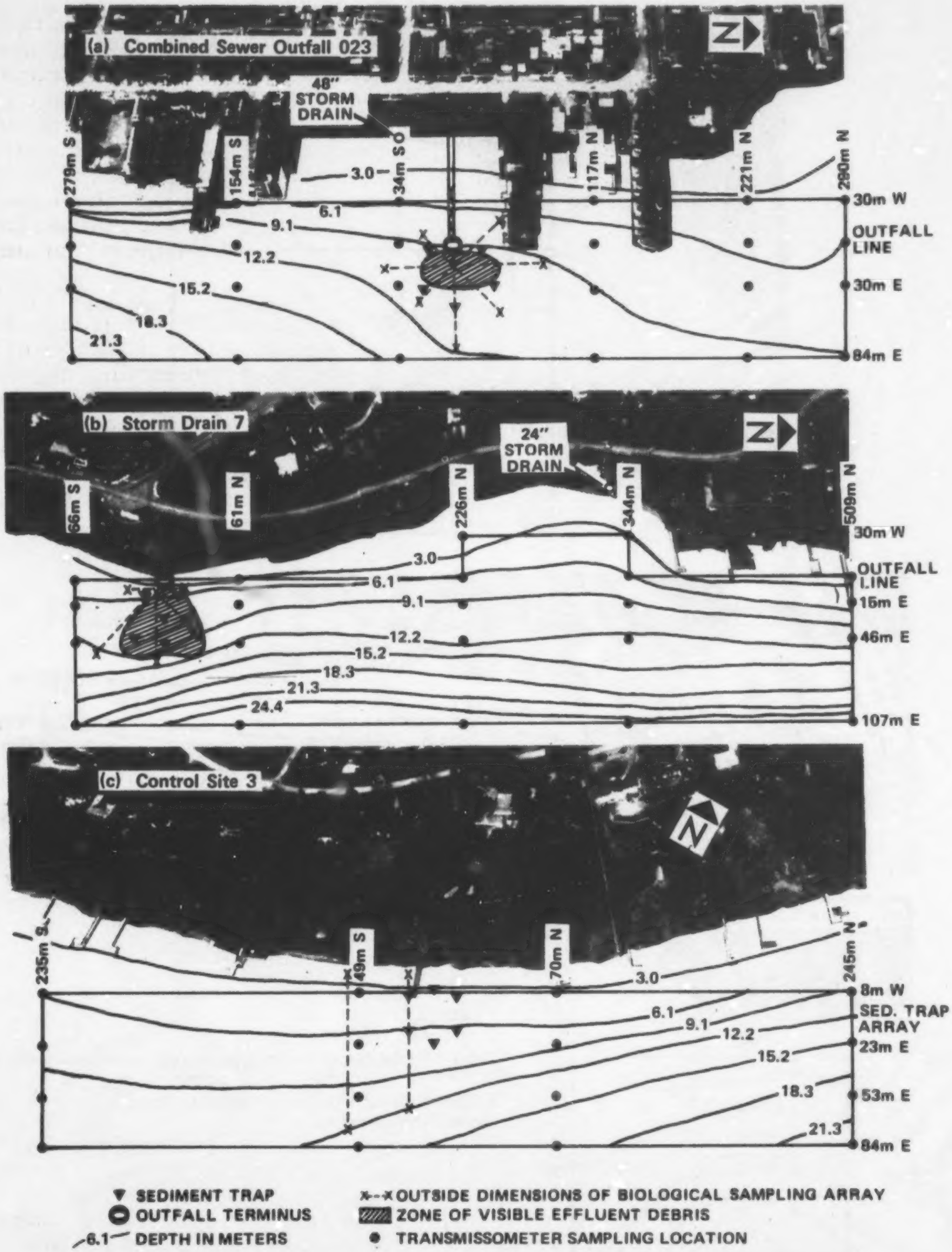

(a) Combined Sewer Outfall 023
48" STORM DRAIN
279m S
154m S
34m SO
117m N
221m N
290m N
30m W
OUTFALL LINE
30m E
84m E
3.0
6.1
9.1
12.2
15.2
18.3
21.3
(b) Storm Drain 7
24" STORM DRAIN
66m S
61m N
226m N
344m N
509m N
30m W
OUTFALL LINE
15m E
46m E
107m E
3.0
6.1
9.1
12.2
15.2
18.3
21.3
24.4
(c) Control Site 3
235m S
49m S
70m N
245m N
8m W
SED. TRAP ARRAY
23m E
53m E
84m E
3.0
6.1
9.1
12.2
15.2
18.3
21.3
N
▼ SEDIMENT TRAP
○ OUTFALL TERMINUS
6.1 DEPTH IN METERS
x--x OUTSIDE DIMENSIONS OF BIOLOGICAL SAMPLING ARRAY
▨ ZONE OF VISIBLE EFFLUENT DEBRIS
● TRANSMISSOMETER SAMPLING LOCATION

Figure 3. Principal set of intensive sampling sites in Lake Washington.

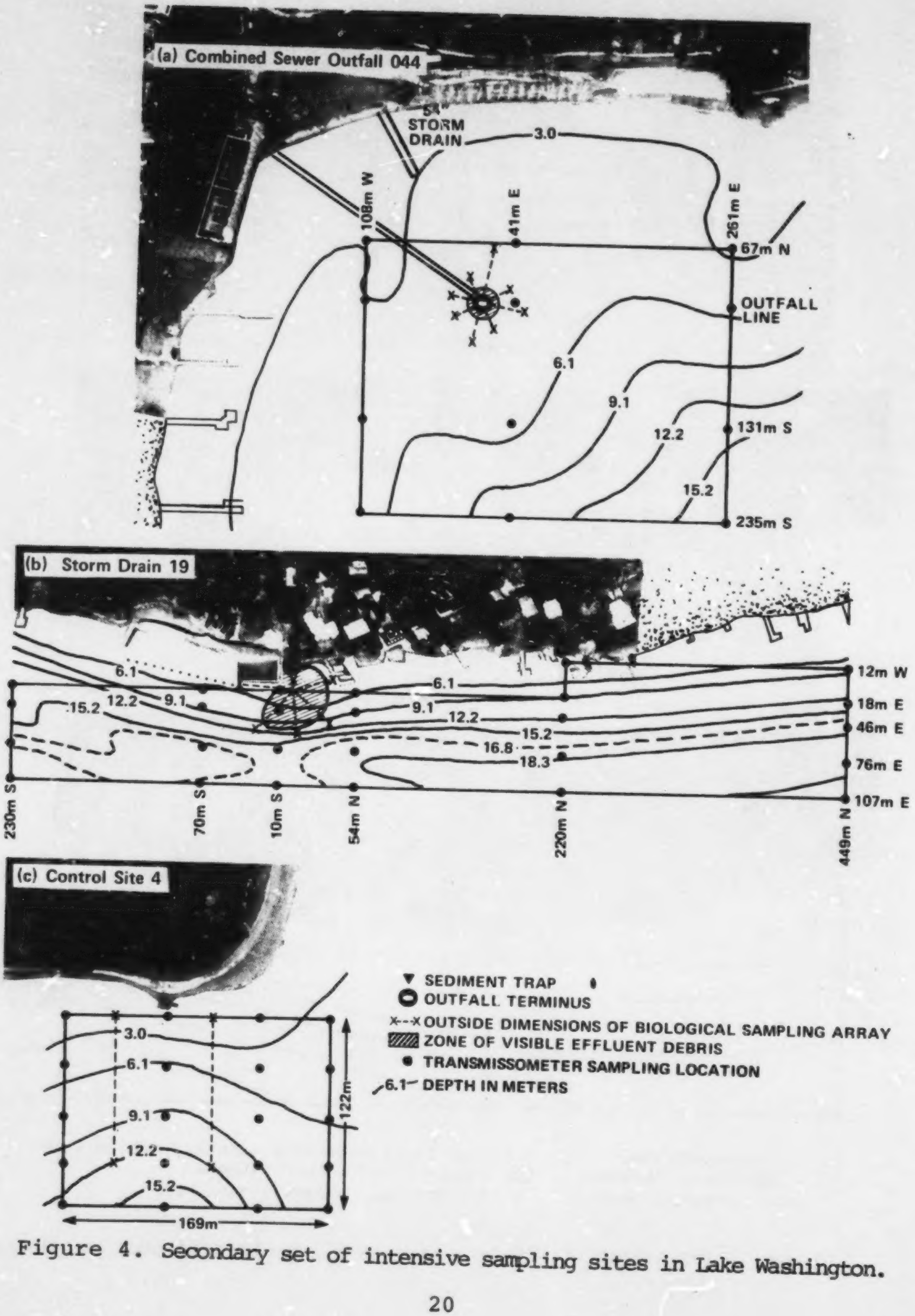

(a) Combined Sewer Outfall 044
54" STORM DRAIN
3.0
108m W
41m E
261m E
67m N
OUTFALL LINE
6.1
9.1
12.2
131m S
15.2
235m S
(b) Storm Drain 19
6.1
15.2
12.2
9.1
6.1
9.1
12.2
15.2
16.8
18.3
12m W
18m E
46m E
76m E
107m E
230m S
70m S
10m S
54m N
220m N
449m N
(c) Control Site 4
3.0
6.1
9.1
12.2
15.2
122m
169m
▼ SEDIMENT TRAP
OUTFALL TERMINUS
X--X OUTSIDE DIMENSIONS OF BIOLOGICAL SAMPLING ARRAY
▨ ZONE OF VISIBLE EFFLUENT DEBRIS
● TRANSMISSOMETER SAMPLING LOCATION
6.1 DEPTH IN METERS

Figure 4. Secondary set of intensive sampling sites in Lake Washington.

north (Figure 5). The intertidal region is primarily made up of a steeply sloping man-made boulder sea wall which extends from a point above Higher High Water down into the subtidal. This wall is interrupted by two small coves. The coves consist of a gently sloping beach comprised of mixed sand, silt and cobble substrata. The CSO conduit is located in the southernmost of the two coves. The base of the conduit is positioned at about +2 feet above MLLW (tidal heights will be referred to hereafter as feet above MLLW). An area of scouring due to flows from the CSO is evident and runs seaward from the base of the conduit to the waters edge at low tide (i.e., at least +0). This scoured area was termed the "wash out" zone by Armstrong et al. (1978). The sediment is finer grained there, and debris is usually piled at the base of the conduit in this zone. The boulder wall and coves form the shoreline of a public park.

In Figure 5 are shown the locations of all of the sample sites. These are the same as those sampled by Armstrong et al., with some exceptions: 1) the subtidal sites at 24 m depth were not sampled by us because no impact was evident in the previous study; 2) the transect numbers for the subtidal sites at 9 m and 13 m were made consistent with their relative position with respect to the CSO (see Armstrong et al., Figure 4); and, 3) new sites were established for sampling Enteromorpha.

FIELD SAMPLING METHODS

Combined Sewer and Storm Drain Discharges

Quantity and Quality --
For selected rainstorms, the overflow discharges at Combined Sewer Outfall (CSO) 023, Storm Drain (SD) 7 and the Denny Way Regulator (refer to Figure 2 for locations) were sampled for loading analysis of suspended solids, metals, total organic carbon, total phosphorus, oils and greases, and total chlorinated hydrocarbons. Automatic sequential samplers triggered by pressure switches were used in conjunction with Arkon pressure-driven flow recorders to provide 2 l samples at regular intervals during the overflows. The sampling intervals were chosen according to the speed of flow response in each system, so that samples would be taken that were representative of all of the major high and low points on the overflow hydrographs.

Plume Distributions --
During a given storm a grid of up to 42 stations (at Denny Way) was covered at each sample site; at each grid point a Martek Model XAS Transmissometer was lowered to the bottom, giving a real-time plot of percent light transmission versus depth on a shipboard XY plotter. Each cast took a maximum of two minutes (to a maximum depth of 24 m (80 feet), with a complete grid coverage requiring about one hour in

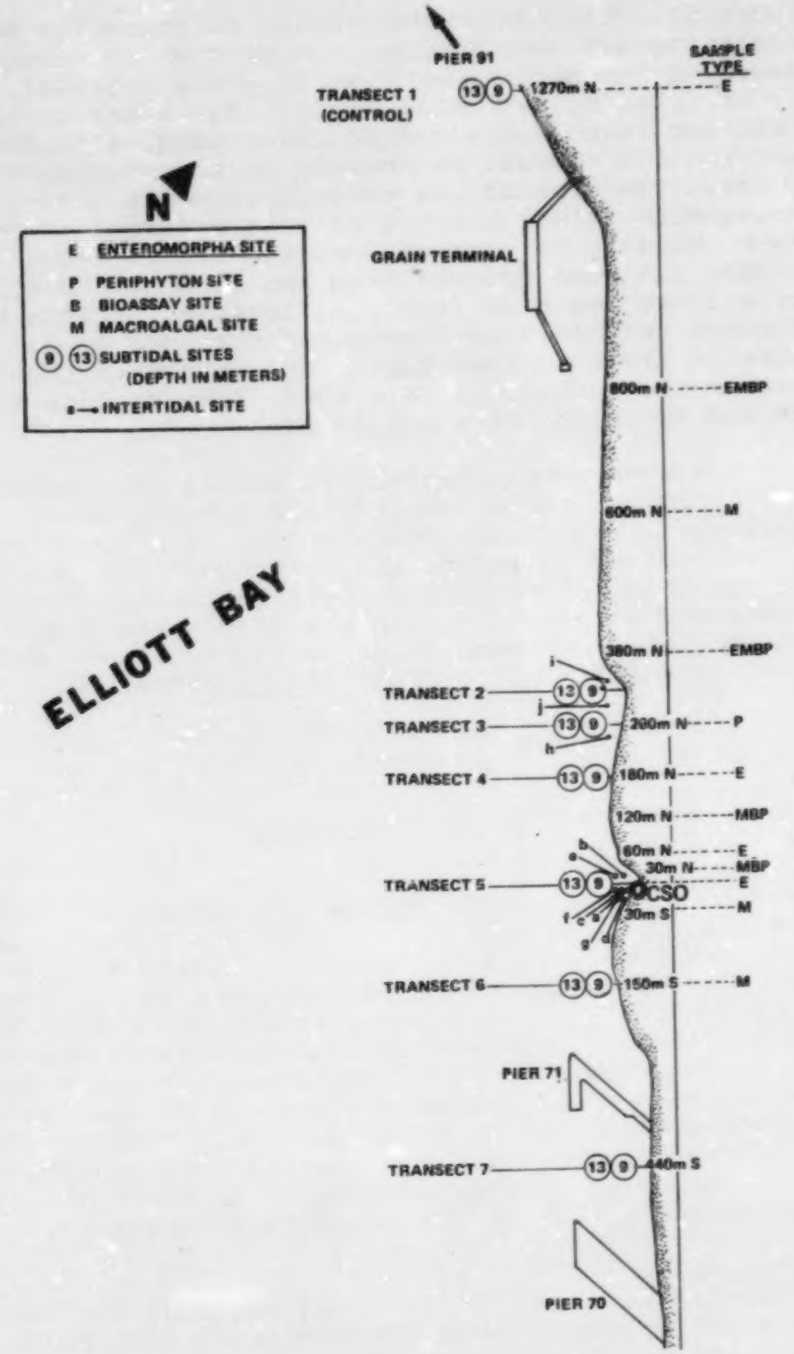

PIER 91
SAMPLE TYPE
TRANSECT 1 (CONTROL)
13
9
1270m N
E
N
E ENTEROMORPHA SITE
P PERIPHYTON SITE
B BIOASSAY SITE
M MACROALGAL SITE
9 13 SUBTIDAL SITES (DEPTH IN METERS)
a INTERTIDAL SITE
GRAIN TERMINAL
800m N
EMBP
600m N
M
ELLIOTT BAY
380m N
EMBP
TRANSECT 2
TRANSECT 3
200m N
P
TRANSECT 4
180m N
E
120m N
MBP
60m N
E
30m N
MBP
TRANSECT 5
CSO
E
30m S
M
TRANSECT 6
150m S
M
PIER 71
TRANSECT 7
440m S
PIER 70
a
b
c
d
e
f
g
h
i
j

Figure 5. Details of sampling transects around the Denny Way Regulator Outfall, 1978.

the lake and two and one-half hours at Denny Way. Whenever possible, each station was visited more than once to measure various stages of the plume development and dispersion.

For grid-site location, a one-time survey was carried out wherein onshore-offshore transects were established visually using landmarks. Rangefinder distances were then determined along these transects using buoy markers when needed. Depth readings from the shipboard depth finder were recorded for each point, and used for all subsequent outings to determine station locations along the transect. The estimated maximum positional error for the stations farthest offshore was 15 m and was somewhat less for inshore stations.

Temperature and oxygen probes were mounted on the transmissometer and were used to periodically check the stratification of the water column. These sensors were interfaced to a Martek Mark V Water Quality Monitor and an X-Y plotter. Both units were lab-calibrated prior to use in the field.

Particle Size Distributions --
The solids grain-size samples of overflow discharge were collected from a single overflow at CSO 023, SD 7 and Denny Way. Single, manual grab samples were taken from the CSO 023 and SD 7 facilities, whereas that from Denny Way was sampled over a five-day period using three automatic composite samplers. Nearly 750 l of effluent were collected at each station.

Settling Particulates

Settling particulate matter was sampled continuously from 1/30/78 to 1/29/79 near the wastewater outfalls at CSO 023 and SD 7 and from 10 to 60 m offshore at the Control 3 site (Figure 2). The sampling devices, or sediment traps, consisted of 30 cm X 30 cm polyvinyl chloride platforms, which held four 10 cm diameter funnels joined to 50 ml centrifuge tubes (Figure 6). Each trap collected a total area of 314 cm^2, all parts of the platforms (including screws) were made of plastic to limit metals contamination. Rigging lines were passed through the center of each trap platform and connected to two polyurethane floats above the collection surface and to a concrete anchor below. This configuration kept the collection surface 2 m from the lake bottom. Thin nylon support lines radiating from the central line to each corner of the trap platforms served to keep the collection surface level in the water column. For each collection period, the traps were serviced and cleaned, with retrieval and reset being done by SCUBA divers. This method of collection was designed to minimize stirring of the lake bottom sediments.

The sediment trap arrays used for CSO 023, SD 7 and C 3 are

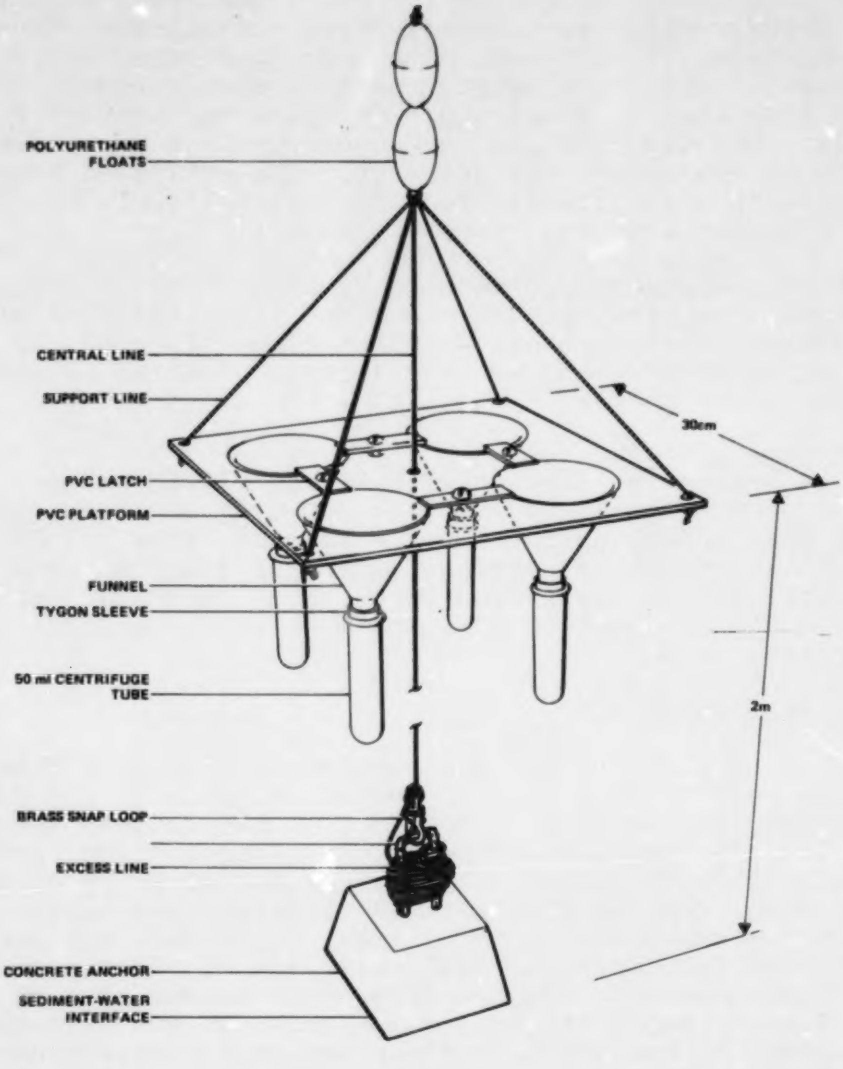

POLYURETHANE FLOATS
CENTRAL LINE
SUPPORT LINE
PVC LATCH
PVC PLATFORM
FUNNEL
TYGON SLEEVE
50 ml CENTRIFUGE TUBE
BRASS SNAP LOOP
EXCESS LINE
CONCRETE ANCHOR
SEDIMENT-WATER INTERFACE
30cm
2m

Figure 6. Details of sediment trap configuration.

shown in Figure 7. Sediment trap placement was determined using the visual and photographic observations of the divers. The rather distinct line of transition between the two types of sedimentary material was denoted the plume boundary.

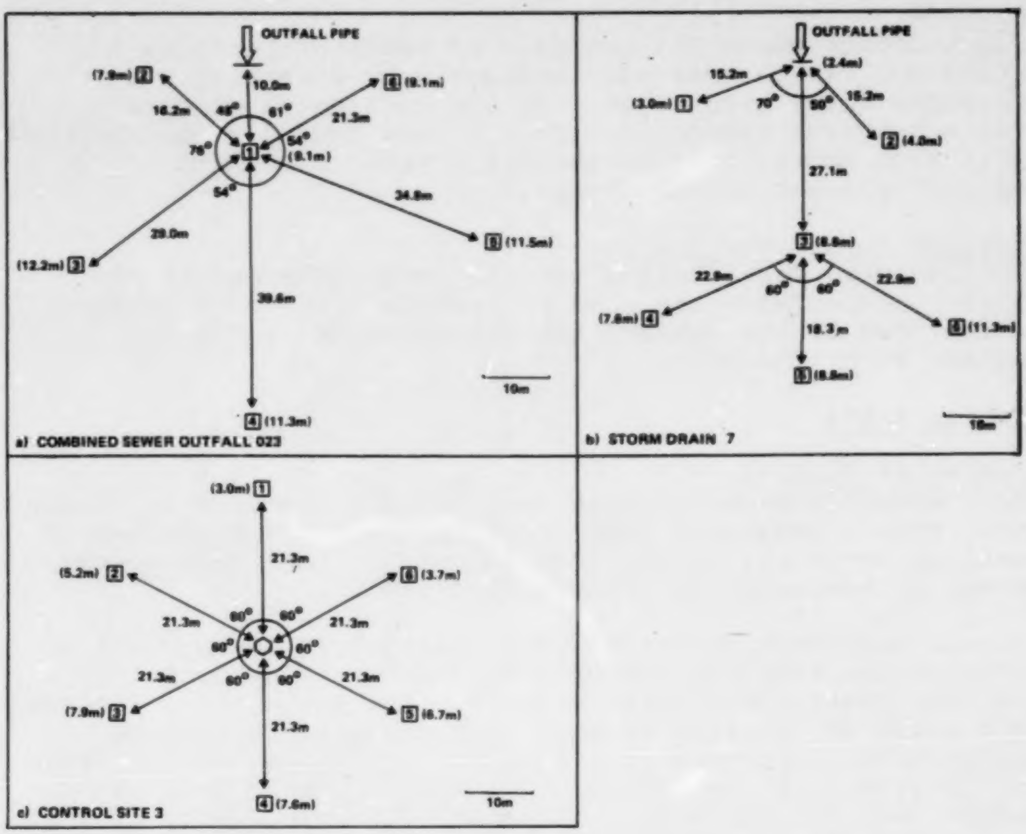

OUTFALL PIPE
(7.9m) 2
16.2m
48°
10.0m
61°
6 (9.1m)
21.3m
78°
1
54°
(9.1m)
54°
34.8m
29.0m
5 (11.5m)
(12.2m) 3
39.6m
10m
4 (11.3m)
a) COMBINED SEWER OUTFALL 023
OUTFALL PIPE
(2.4m)
15.2m
(3.0m) 1
70°
50°
15.2m
2 (4.0m)
27.1m
3 (8.8m)
22.9m
60°
60°
22.9m
(7.8m) 4
18.3m
6 (11.3m)
5 (8.8m)
10m
b) STORM DRAIN 7
(3.0m) 1
21.3m
(5.2m) 2
6 (3.7m)
21.3m
60°
60°
21.3m
60°
60°
21.3m
60°
60°
21.3m
(7.9m) 3
5 (6.7m)
21.3m
4 (7.6m)
10m
c) CONTROL SITE 3

Figure 7. Configurations of the sediment trap arrays moored at the principal sampling sites in Lake Washington. The positions of the traps are indicated by boxed numbers. The values in parentheses are the location depths.

Sediments

Surface Samples --

Sampling for preliminary analyses of the freshwater sediments was carried out by SCUBA divers. Each station was initially surveyed as to depth and bottom contours, nature and condition of the outfall pipe, extent of apparent debris accumulation and proximity and nature of interfering structures. At each CSO and SD, duplicate samples of the surface 3 cm of the (apparently) most highly contaminated sediments were collected in specially-prepared 110 cm^3 glass cylinders closed at each end with rubber stoppers. For the sake of chlorinated hydrocarbon/PCB analyses, the stoppers of one of each set were covered with aluminum foil. For the aluminum analyses the stoppers of the other were left bare.

Cores --

Lake sediment cores for analysis of sediment profiles of metals and carbon were also collected by divers at the transmissometer grid sites. Thirty cm lengths of clear tenite butyrate tubing (3.5 cm ID) were used for this purpose. Cores from depths greater than 15 m were taken with a 7 kg modified Phleger gravity corer.

Particle Size Distributions --

Particle size distribution samples were collected by the divers just outside the area of visible overflow influence at the ends of the outfall structures at Denny Way and Madison Park (CSO 023).

Benthic Biota

Freshwater Studies --

The freshwater benthic biota were manually sampled by divers using white, polyvinyl chloride core tubes. This method of sampling meets all of the requirements of the ideal sampling device as described by Brinkhurst (1974).

Several important questions were resolved in the process of refining the sampling methods, including the selection of the most appropriate core dimensions and the number of cores that would be required at each sampling site to provide statistical confidence in the data. Brinkhurst (1974) feels that only a small percentage of animals live in sediment deeper than the top 6 cm. In order to sample nearly 100% of the organisms at the site, 15.3 cm was chosen as the depth of core penetration. The core tube diameter was 2.9 cm.

An adaptation of the techniques used by English (1964) was used in a preliminary study to determine the number of cores to be taken at each sampling site. For this work, 20 cores were collected from each of several sites within a selected nearshore area. Means for chironomid, oligochaete, and copepod counts were calculated for each core and confidence intervals were calculated for each number of cores ranging from one to the maximum number taken. By expressing the confidence intervals as percentages of the sample mean we were able to choose the most cost-effective yet statistically acceptable number of cores to be taken at each site.

Twenty cores of each of two experimental diameters (29 and 38 mm) were taken from each of three depths - 1.5, 4.6 and 7.6 meters. Core locations in an 81-division, 0.5 m^2 wire sampling grid were chosen for each depth with the aid of random number tables. The contents from each tube were preserved with 10% formalin, and stained with Phloxine B dye.

Due to documented seasonal differences in the populations of benthic organisms (Patten et al., 1976), sampling was carried out during two seasons. The February sampling period was chosen as a period optimum for detecting pre-emergence conditions. The late summer or fall period was chosen as the optimum time for post-emergence observations.

In all areas, station depths and distances from the outfall were located by divers. The transect line was generally anchored at the center sampling station and placed at the desired angle from the shoreline. The divers proceeded along the transect line to the desired station depth where the distance was recorded. The 0.5 m^2 (81-division) sampling grid was placed at each sampling station and eight core tubes (to assure six cores) were inserted into the predetermined grid compartments. Core tubes were marked with grid location designations selected from random number tables. On the boat, the samples were emptied into plastic bags and preserved with full strength formaldehyde mixed with the water in each sample to form a standard 10% formalin solution. In the laboratory, organisms from the cores were counted, sorted and preserved in 70% isopropanol.

Marine Studies --

In situ bioassay studies were started at the marine CSO (Denny Way) during February, 1978. Two hundred individuals each of the blue mussel, *Mytilus edulis*, and the Pacific oyster, *Crassostrea gigas*, were place in four dome-shaped plastic crab pots (22 cm high X 60 cm across), and anchored at Mean Lower Low Water (MLLW) at various distances from the outfall (indicated by Bs in Figure 5). Eight to ten individuals of each species were removed monthly for condition index analyses (refer to laboratory methodology for details). In addition, extra specimens were collected during February and April, 1978 for trace metals analysis.

The length-width relationship of the green alga *Enteromorpha intestinalis* was studied because previous observations from samples along the boulder wall had indicated a correlation between distance from the CSO and the length-width ratio as a measure of growth. Increased growth rates of a closely-related species (*E. prolifera tubulosa*) have been observed in areas inundated by wastewater (Tewari, 1972). Collections were made at each site by carefully scraping a number of individuals off of the hard substrata. These were placed in plastic vials and preserved in 5% formalin. The sampling was conducted in April and August of 1978.

To sample periphyton communities, blocks made of half pumice and half concrete with a flat surface area of at least 450 cm^2 were placed at Mean Low Low Water (MLLW) at various distances from the CSO. At this tidal level, diatoms are generally the most abundant alga by cover. The periphyton that attached to the blocks was sampled in April after about four weeks of exposure. The periphyton was brushed into glass jars with a stiff toothbrush, and preserved in 5% formalin.

The epibenthic community that attached to the boulder wall at MLLW was sampled at various sites in April and August. A 0.06 m^2 plexiglass plate with 20 randomly-located points was tossed non-selectively 20 times in the region around each site. The taxa that occurred under each point within each quadrat were identified and given a score equal to the number of points which covered the entity. Taxa that occurred within the quadrat but not under a point were identified and given a score of one.

Intertidal soft substrata infauna were sampled during April and August at seven sites in the CSO cove and three sites in the control cove to the north (Figure 5). A cylindrical plexiglass tube (31.2 cm^2 in cross-sectional area and 15 cm deep) was used to extract four sediment cores at each location. The sample of sediment was placed in a plastic bag and was then preserved in 10% formalin and stained with Rose Bengal stain. At each site, a 3-5 g sediment sample was taken for volatile organic analysis.

The subtidal infauna was sampled at two depths along seven transects during April and August (Figure 5). Collections of bottom sediments were made with a 0.1 m^2 Van Veen benthic grab. Two grabs were taken from each site. A 3.5 g sample of the sediment was obtained from the first replicate at each site to be analyzed for volatile organic content. The samples were screened through a 1 mm mesh screen and the material retained on the screen was preserved and stained in 10% formalin and Rose Bengal Stain.

Viruses

For each overflow sample, approximately 285 l of the discharge were pumped from the pipe into a 380 l polypropylene container. Two equal-volume aliquots (ranging from 76 to 190 l) were subsequently taken from the larger sample for analysis.

Collection methods for the receiving waters were similar. The overflow plumes were first located by light transmission measurements. Approximately 285 l of the most turbid water were then pumped into large polypropylene containers on board the boat and was transported to shore for further processing. Follow-up samples were collected in the same locations 24 hours later.

Three sets of sediment samples were collected at the sediment trap locations at CSO 023 and SD 7; one set was collected at the Control 3 site. The sample material was scooped from the top 2-cm layer with sterilized glass tubes. The first set was collected by divers 7 days after a storm, whereas the second and third and the C 3 samples were taken from Van Veen grabs within one day following a storm.

ANALYTICAL TECHNIQUES

Combined Sewer and Storm Drain Discharges

Quality Analyses --
Individual analyses were performed as follows:

Total Suspended Solids - determined in conjunction with the total chlorinated hydrocarbons analyses, as specified below.

Metals - split sample, acidified one part with concentrated HNO_3. Filtered the other through a .457 µm membrane filter that had been prerinsed with 1% HNO_3 and deionized water. Acidified the filtered sample with concentrated HNO_3. Both samples analyzed for Cu, Pb, Zn, Al on IL Model 453 Atomic Absorption Spectrophotometer, and for Hg on Anti-Pollution Technology Corp. Model 2006-1 Mercometer. Only the unfiltered sample was digested prior to analysis.

Total Phosphorus - split sample, filtered one part through Whatman #40 filter. Acidified both fractions with 0.5 ml 5 N H_2SO_4/50 ml sample. Samples digested as for Cu, Pb, and Zn (aliquots were taken for analysis from the same digestion mixtures). PO_4 measured as orthophosphate by the ascorbic acid method (APHA, 1975).

Chlorinated Hydrocarbons - filtered all of sample (for analysis of particulates only) through muffled, tare-weighed Whatman GF/A glass fiber filters. Filter then dried at 105°C and cooled in desiccator. After final weight was taken the sample was extracted by Soxhlet with acetone for eight hours. Extracts dried, then infused with petroleum ether and concentrated. Cleanup and fractionation of dissolved components done in Florisil columns by elution with various mixtures of ethyl and petroleum ether. Analyses were done by gas chromatography, using a Tracor Model 222 GC fitted with a ^{63}Ni high-temperature electron capture detector.

Oils and Greases - Hexane/Soxhlet extraction method (APHA, 1975).

Total Organic Carbon - Potassium persulfate/phosphoric acid digestion of blended samples in nitrogen-bubbled, sealed ampoules. Resultant CO_2 was conveyed by nitrogen carrier gas through a Model 865 Beckmann Infrared Analyzer. Strip chart peaks were compared to those of similarly-treated standards.

Particle Size Analyses --
The 750 l samples collected from the CSO 023, SD 7 and Denny Way overflow structures were reduced to a total volume of approximately 4 liters each by a succession of settlings and decantings over a period of about one week. Following the initial volume reduction, the samples were refrigerated at 4°C to minimize deterioration.

The testing of the consolidated overflow particulates consisted of organic content and grain-size determinations. The former was estimated by burning off the organic material after first removing the sample moisture by oven drying at 65°C. Grain-size determinations were performed in accordance with ASTM Test Designation D422-63, and included combined coarse sieve and hydrometer analyses. This work was done for Metro by the Seattle laboratory of Converse Davis Dixon Associates, Inc., geotechnical consultants.

Settling Particulates

The sediment trap samples were centrifuged at 9000 rpm for 7 minutes, decanted and dried at 60°C for 36 hours. The samples were then weighed individually and the four samples from each trap were combined and comminuted prior to chemical analysis. One hundred mg subsamples were then digested using $HF\text{-}HNO_3\text{-}HClO_4$ by a procedure similar to that of Bortleson and Lee (1972), except that the entire digestion was done in a single 10 ml teflon crucible (Birch, 1976). An aliquot of this digestrate was used for determination of P, Cu, Pb, Zn and Al.

The analyses were done as follows:

Phosphorus - ascorbic acid molybdenum blue method (APHA, 1975). The mean of duplicates was reported for each sample. The mean coefficient of variation for 14 sets of duplicate digestions was 4.8%.

Copper, Lead and Zinc - digestrate analyzed on an IL Model 353 Atomic Absorption Spectrophotometer. Precision, including subsampling, was within 20%, and generally better than 10%.

Aluminum - two methods: as for Cu, Pb, and Zn, and analysis by neutron activation. For 28 samples, with one subsample analyzed by each method, the mean coefficient of variation was 4.3%.

Carbon - analyses done on 20-100 mg of dried sediment using a Leco induction furnace and carbon analyzer. The results given are the means of two replicates. The mean coefficient of variation for five samples (four replicates each) was 6.0%.

Sediments

Surface Sample Analyses --

The excess water was drained off each of the surface sediment samples collected for the preliminary study, and the sediment was transferred to glass (for PCB and chlorinated hydrocarbon analysis) and polypropylene (for all other analyses) containers. The samples were weighed wet and then oven-dried at 105°C. Aliquots taken for Hg analysis were dried at 50°C to minimize loss through vaporization. All samples were weighed dry when cool.

Individual analyses were performed as follows:

Copper, Lead and Zinc - as for settling particulates. Analyses were done by atomic absorption spectrometry (APHA, 1975) on an Instrument Laboratory Model 353 AAS.

Aluminum - as for settling particulates.

Mercury - dried sediments digested for 1 hour in concentrated H_2SO_4/concentrated HNO_3 mixture, infused with a $KMnO_3/K_2S_2O_8$ mixture and digested for an additional 2 hours. Analyses were done by cold vapor flameless atomic absorption spectrometry using an Anti-Pollution Technology Corp. Model 2006-1 Mercometer.

Total Phosphorus - digestion and analysis as described for discharges.

PCBs/Chlorinated Hydrocarbons - wet sediments extracted and analyzed as described for discharges.

Oil and Greases - Hexane/Soxhlet extraction method (APHA, 1975).

Total Organic Carbon - Preliminary Study: inorganic carbon driven off as CO_2 by acidification of samples to pH = 2.0 with HCl. Residual (organic) carbon measured by a Leco Model WR-11 Total Carbon Analyzer by infrared analysis of

CO_2 produced through sample combustion. Intensive studies: as for settling particulates.

Core Analyses -- The cores were first examined for gross physical characteristics and then extruded and sliced at 0.5 cm and at 1 cm intervals to 12 cm depth. The slices were weighed, dried at 103°C for 24 hours, reweighed, and ground in a Diamonite mortar. Digestion and analysis were done as described for settling particulates on the 0-0.5 cm, 0.5-1 cm, 3-4 cm and 7-8 cm sections. Analysis for chlorinated hydrocarbons was as for discharges. Due to the large number of samples involved, some cores were stored at 5°C for up to one week before processing.

Particle Size Analyses -- The sediment grain size determinations were done using the methodology specified above for the discharge particulates.

Benthic Biota

Freshwater Studies -- For each sampling site at each station, six of the eight cores were randomly selected for benthic organism counts. Four of the six were randomly selected for dry weight analysis. The cores were first washed in a #50 (.297 mm) screen to reduce the amount of sediment. Ten cores from the September sampling period were also selected to test the number of organisms that would pass through a .500 mm screen but not through a .297 mm screen. The results from this test can be used for comparisons between this study and other benthic studies using .500 mm screens.

The February samples were first screened and then placed in bottles of 70% isopropanol. Sorting and counting took place within several days. Organisms from approximately half of the samples were counted and identified at the same time that the organisms were separated from the sediment. For the remaining cores the organisms were separated from the sediment and stored for identification and counting at a later date.

The weighing of the February samples was delayed until all counting and sorting was completed. Most of the organisms from the September samples, however, were counted, sorted and weighed immediately after screening. Whereas it was recognized that significant weight loss can occur for benthic organisms while stored in preservatives, each of the two seasonal lots received consistent treatment within itself, and no between-season weight comparisons were made.

Organisms were separated from the sediment using binocular dissecting microscopes. Identification was done with the aid of taxonomic keys by Pennak (1953). No attempt was made to identify organisms to the species level.

Oligochaetes (aquatic earthworms) and nematodes (roundworms) were counted only if the organisms were intact because head and tail pieces were not clearly distinguishable. Worm parts, however, were included in the dry weights. Although it was anticipated that such a dichotomy of quantifying procedures could weaken count-to-weight comparisons, this was considered unavoidable due to time and task constraints. No eggs, egg cases, empty shells or empty exoskeletons were counted or weighed except for mature oligochaetes found in egg cases.

Some organisms present in the samples were not counted or weighed. Ostracods (seed shrimps) were recorded as either present or absent, but were neither counted nor weighed because they occurred in high numbers in most samples, were difficult to pick out, and are usually neglected by benthic researchers in freshwater. Terrestrial insects and larval fish found in some of the core samples were not quantified because they are not normally considered benthic organisms. Organisms in the Order Cladocera (water fleas) were likewise ignored because they are generally described as zooplankters and not benthic organisms.

Some members of the Family Spongillidae (freshwater sponges) were also observed in the benthic cores. These were not counted or weighed because identification was difficult and the size and thickness of a single sponge was highly variable. Pennak (1953) states that sponges are generally associated more with hard substrates than with muddy substrates. Therefore, changes in the numbers or weights of sponges in our core samples would probably be related more to substrate than to pollution impacts.

Dry weights were obtained for samples dried at 80°C for 24 hours. The samples were held in a desiccator between drying and weighing. The dry weights for each core were divided into three categories: oligochaetes, chironomid and ceratopogonid larvae, and the rest of the benthic organisms combined. Weight data were important for oligochaetes because many oligochaete parts, representing a significant part of the dry weight, were not included in the oligochaete counts. Weight data were important for both oligochaetes and chironomid larvae because they generally vary in size more than the other benthic organisms and they are both important food items for fish. In general, ceratopogonid and chironomid larvae were counted separately, but both groups were combined and weighed together because of their taxonomic and physical similarities. The dry weights of all groups were combined and used as an indication of the total biomass at each sampling station.

Marine Studies --
A condition index (CI) (Westly, 1961; Quayle, 1969) was determined periodically for composite samples of 8-10 individuals of each of the two mollusc species, Mytilus edulis (blue Mussel) and Crassostrea gigas (Pacific oyster). The index describes the plumpness of bivalves, and has been used to monitor environmental conditions (Wass, 1967).

The condition index analysis was first done at the time of experiment initiation, and monthly thereafter. For the February and April samples, the concentrations of Pb, Zn, and Cu were also determined for both species; this was done by atomic absorption spectrometry following hot digestion in successive baths of concentrated HNO_3 and $HClO_4$.

For each periphyton sample, a wet microscope slide mount was made of a small subsample of the material. The first 200 cells that were encountered on the slide at a magnification of 200X under a compound microscope were counted and identified (usually to genus). Three subsamples were analyzed from each sample.

The length-width ratios of the samples of the green alga, Enteromorpha intestinalis, were determined for 50 randomly-selected individuals per sample using a dissecting microscope with an ocular micrometer at 120X.

All intertidal infauna samples were rescreened through a 1 mm screen and rinsed with tap water to remove the formalin. All organisms retained on the screen were identified and counted. Subtidal infauna were sampled in April and August.

Volatile organic contents of both intertidal and subtidal sediments were determined using the 3-5 g sample obtained at the infauna sample sites. Each sample was dried for 30 hr at 100°C, weighed, burned for three hr at 550°C, and reweighed. The loss of weight, expressed at a percentage of the dry weight, gave a rough estimate of the organic carbon present in the sediments (Morgans, 1956).

Viruses

From each of the original discharge samples, two equal-volume aliquots (ranging from 76 to 190 liters) were taken concurrently for virus analysis. One of these samples consisted only of the overflow water. To the other sample a known level of seed virus was continuously added, and both samples were subsequently passed through the filtration apparatus. From these two samples the percent recovery of virus was calculated.

Viruses were concentrated by a modified version of the tentative standard method of finished waters described in

APHA (1975). Sample water was first passed through an orlon prefilter (Orlon Depth Filter No. 019R10S, Commercial Filters Division, The Carborundum Company, Lebanon, Indiana) for removal of abrasive particulate matter. The pH of the water was adjusted to 3.5 by addition of HCl solution with a Johanson proportioner. Aluminum chloride was concurrently added by proportioner to a final concentration of .005 M. The conditioned water was then passed across a series of virus-adsorbing filters consisting of a fiberglas-wound depth filter (No. K27R10S, Commercial Filters Division, Carborundum) and a series of three epoxy-fiberglas filter tubes of 8.0 µm porosity (Grade C filter, Balston, Inc., Lexington, Massachusetts).

After collection of each sample, residual sewage was evacuated from all of the filters with forced air. The orlon prefilter was then rinsed under pressure with 800 ml of sterile physiological saline adjusted to pH=3.5 with HCl. Virus-adsorbing filters were rinsed with 1,200 ml of an identical saline solution. Viruses were then eluted from the prefilter with 800 ml of a sterile .05 M glycine solution adjusted to pH=11.5. Viruses were eluted from the virus adsorbing filters with 1,200 ml of an identical glycine solution. The pH of each eluate was adjusted to approximately 8.5 with sterile .05 M glycine (pH=1.5) immediately after passage through the filters. This latter step helped prevent inactivation of viruses at the high pH. The eluates from the prefilter and virus-adsorbing filters of each sample were then combined for reconcentration of viruses.

The virus reconcentration procedures followed were a modified combination of those suggested by The Carborundum Company and Farrah et al.(1976). Aluminum chloride was added to each sample eluate to a final concentration of .003 M. The pH was raised to 7.0 by addition of 1.0 M sodium carbonate. A floc formed that trapped or adsorbed viruses and settled to the bottom of the container. The floc was allowed to settle for one-half hour and then collected and centrifuged at 4,000 X g for 20 min. The supernatant was discarded, and the viruses were eluted from the floc with fetal calf serum adjusted to pH=11.5 and containing .01 M EDTA. Enough of the calf serum was mixed vigorously with the floc until a pH of 9.5 was obtained. This mixture was centrifuged at 15,000 x g for 10 min. The virus-containing supernatant was saved and adjusted to pH=7.4, Hanks' balanced salts were added and the resulting solution was stored at 70°C until time of assay. The range of sample volumes was about 50-100 ml.

The procedures used in processing the sediment samples for viruses were as described by Smith et al. (1978). At the time of the virus assay the samples were rapidly thawed in a water bath and chloroform added to 10% v/v to rid the sample of bacteria and fungi. Prior to inoculation onto cells, we removed a portion of the sample and allowed it to stand at 37°C for one hour to facilitate evaporation of any residual chloroform; this aliquot was then used as the inoculum.

Buffalo Green Monkey (BGM) cells were used for the virus assays. Stock cultures of cells were grown for seven days with the medium changed on the fourth day. The growth medium was comprised of Minimal Essential Media (Eagle) with Hanks' salts, L-15 (Leibovitz medium), 1.5 mg/ml $NaHCO_3$, 0.5 mg/ml amphotercin B, 10% fetal calf serum, 100 units/ml penicillin G and 100 g/ml streptomycin sulfate. Each of twenty 25-cm^2 flasks containing BGM cells grown for four days at 37°C was inoculated with 0.2 ml of sample (4.0 ml total per sample). Viruses were allowed to adsorb to the cells for 1.5 hr at 37°C prior to overlay with an agar medium. The overlay medium consisted of Minimal Essential Media (Eagle) with Hanks' salts, 1.5 mg/ml $NaHCO_3$, 0.5 g/ml amphotercin B, 100 units/ml penicillin G, .025 g/ml $MgCl_2$, 0.6 percent neutral red (1:300), 1% purified agar and 1% fetal calf serum. Flasks were incubated for seven days at 37°C, and plaques were counted on days 3 through 7.

DATA REDUCTION

Combined Sewer and Storm Drain Discharges

Pollutant Loading --

Estimates of total loading for each measured parameter for each outfall for each storm were made with the aid of a computer program designed to calculate a time integral product of concentration times flow for each storm hydrograph. To this end the flow data were entered as values measured at regular intervals throughout. The quality analyses were less abundant, being limited specifically to the significant features of the hydrograph, i.e., the highs, the lows, and the initial and final ascending and descending limbs. Between these points, values were interpolated to complement the flows given at regular intervals. A storm was defined as a minimum total of .08 cm of rain separated from preceding and succeeding measurable rainfall by a minimum of three hours.

Single quality samples contained insufficient particulate material for chlorinated hydrocarbon analyses. As a result, sequential samples were composited to represent specific features on the hydrographs. With the exception of the final storm monitored at each of the three principal outfalls, CSO 023, SD 7 and Denny Way, the sediment loading values were likewise calculated from storm segment composites.

For the storm drain, where a dry weather base flow is discharged, pollutant mass loadings were calculated for both the base flow and the storm washoff--the latter being determined as the difference between the total storm load and the base load estimated from preceding flows and concentrations. Total rainfall volume on each service area was also determined.

Plume Distributions --

The vertical profiles of light transmission versus depth for storms monitored were digitized and keypunched for computer contouring. For contouring purposes, an interpolative contouring routine was used to fit a bivariate elastic spline surface to the initially coarse raw data grid, resulting in smooth contour output. This program was a modified version of a program described in Numerical Plotting System User's Manual No. W00053 (University of Washington, August, 1977). Beyond this, the plots were graphically enhanced for report presentation.

Settling Particulates and Sediments

Means, standard deviation, correlation coefficients and analyses of variance were calculated with the exclusion of measurements more than three standard deviations from the mean because a few very extreme values obscured any meaningful comparisons. Two-way analyses of variance required equal numbers of measurements in each cell and therefore Monte-Carlo simulation techniques (Wallis et al., 1974) were used to insert non-biased data points.

Comparisons between station means for sediment core surface segments were made using Scheffe's procedure for linear contrasts (Scheffe, 1959). The levels of significance of correlation coefficients for sediment core segments and sediment trap samples were found using the Student's t distribution.

The information provided by the sediment particle size distribution analyses was reduced to four values for each sample: organic content, median particle diameter(M_2), sorting coefficient (S_o) and skewness(S_k). As described by Sverdrup et al. (1942), the latter three parameters collectively describe the shape of a size distribution curve.

Benthic Biota

Freshwater Studies --

The primary purpose of the preliminary study done relative to the benthic biota was to determine the most time- and cost-effective number of cores to be collected at each station for biota distribution analyses. To this end, a complete statistical analysis was performed on chironomid larvae, oligochaete and copepod counts for stations located at 1.5, 4.6 and 7.6 m depths. These organisms were selected on the basis of their high numbers and importance in the littoral food chain.

For each station sampled (20 cores/station), a log (X+1) transformation was made on the raw counts (Xs), because the variance (S^2) greatly exceeded the mean, indicating a negative binomial distribution. The 95% confidence limits were calculated for each n (number of cores) from one to twenty, using the formula

$$\bar{X} \pm t_{.05(n-1)} \sqrt{S^2/n}$$

The resultant values of $\bar{X}$ and the confidence limits were then transposed back to the original scale and the confidence limits for values of $\bar{X}$ representing 1-20 cores were expressed as fractions of $\bar{X}$. The number of cores to be collected per station was determined as the most useful balance between statistical reliability and sample handling time.

For the principal project studies, linear regression analyses were run for the organisms that were either important in the food chain of fishes, or found in high numbers in our samples (Nie et al., 1975). For Control Stations 3 and 4, linear regressions were run using weights and/or transformed counts (log (X+1)) as the dependent variable (Y) and the depth of the sampling station as the independent variable (X). This was done to establish the strength of the depth effect in a relatively unaffected or control area. For CSOs, however, distance from the source of discharge was used as the independent variable (X). This was done to test for possible effects of pollution that might be stronger near the discharge source. For SDs, stepwise multiple regressions were run using weights or transformed counts as the dependent variable (Y) and depths and distances as the independent variables (X_1 and X_2). With the aid of multiple regression techniques, the relationships between variables were separated or combined as necessary to investigate all possible relationships. Multiple regressions were not run with the CSO because the majority of sampling stations in each area were the same depth.

When the regression equations were not statistically significant ($\alpha = .05$ level), the means of the raw counts and dry weights were used for comparisons. The predicted values used in this report represent the average value at each site (with 95% confidence) that would be obtained by multiple sampling at each site. This provides a statistical measure of the increases or decreases in the numbers and biomass of benthic organisms relative to depth and distance from the study outfalls.

Correlation coefficients (r), coefficients of determination (r^2), and the significance level of the regression equations were used as measures or indicators of the strength of the relationships between the count and weight data vs. the depth and distance factors. The "r" value indicates the "degree of association" between variables (Zar, 1974). An r of 1.00 or -1.00 indicates a perfect association between variables whereas an r value of 0.00 indicates no association whatsoever. The value of r^2 is the fraction of the total variation in Y (counts or weights) that is explained by the fitted regression.

Marine Studies --

Species-richness curves (Hurlbert, 1971) were calculated on the combination of data from all replicates at a site for the periphyton, boulder wall algae, subtidal polychaetes and subtidal molluscs. The multivariate technique of discriminant analysis was used to statistically evaluate sites using periphyton and boulder wall community data. Discriminant analysis weighs and combines the discriminating variables (i.e., species counts) in such a way as to force the groups to be as statistically distinct as possible. The species that are most important in discriminating among sites are indicated by tests of significance based on a linear combination of all species values. A computer program (BMDO7M, Dixon, 1973) performed this analysis. The part of the output used consisted of (1) the mean and standard deviations of species values at each site, (2) the proportion of variation explained by the canonical variables associated with the analysis, (3) the rank order of species according to their entrance into the discriminant function, and (4) a plot of the samples along canonical variables one and two.

Classification analysis was used to compare subtidal samples within each season. After the dissimilarity of the sites (Bray-Curtis coefficient, Clifford and Stevenson, 1975) was calculated based on square root-transformed species-abundance values, the sites were clustered using the group-average sorting strategy (Sokal and Michener, 1958). The 20 most abundant species were used in the analysis each season. The results of this analysis are presented in the form of dendrograms.

The proportion of individuals within the phyla Arthropoda, Mollusca, and Annelida at each of the subtidal sites was determined and graphically compared using the methods of Snee (1974). The proportions of feeding types (after Jumars and Fauchald, 1976) of polychaetes at each site were also compared using this method.

SECTION 5

RESULTS

FRESHWATER STUDIES

Preliminary Studies

To aid in the selection of CSO and SD sites for more intensive study, levels of contaminants in near-outfall sediments were assessed for the Preliminary Study stations (Figure 2). A summary of the resultant data is presented in Appendix A, Table A-1. In all cases, the samples represent surface sediments collected by divers at the near-outfall locations thought to have the maximum potential for contamination by the discharge particulates.

Figure 8 represents an attempt to composite the information presented in Table A-1. The "sediment enrichment factors" are given for three categories of parameters: (1) organics (total organic carbon plus oils and greases) and total phosphorus, (2) metals (Cu, Pb, Zn, Hg), and (3) chlorinated hydrocarbons and PCBs. To calculate these relationships mean values were derived for each parameter at each station, and the resultant figures were normalized by parameter, i.e., the lowest value found for each parameter was divided into each of the corresponding values from the other 28 stations. These figures were then added for each station for each category, and the sums were in turn normalized within the categories. Thus, the total length of the three histogram bars at each station divided by 3.0 would give the overall enrichment of that station compared to a hypothetical composite of the most pristine sediments found in the lake. The sediments from CSO 046, which does not appear to overflow, approach this quality overall. The actual background standards used for the Figure 8 calulations were: organics and total phosphorus - Station CSO 046, metals - Station C 10, and chlorinated hydrocarbons (ClHCs) and PCBs - Station C 3. These values were all comparable to or lower than those determined for pre-1900 core segments collected in the deep portion of the lake by Birch (1976) and Spyridakis and Barnes (1976). In terms of low concentrations, Station CSO 046 was also second in both metals and ClHCs and PCBs.

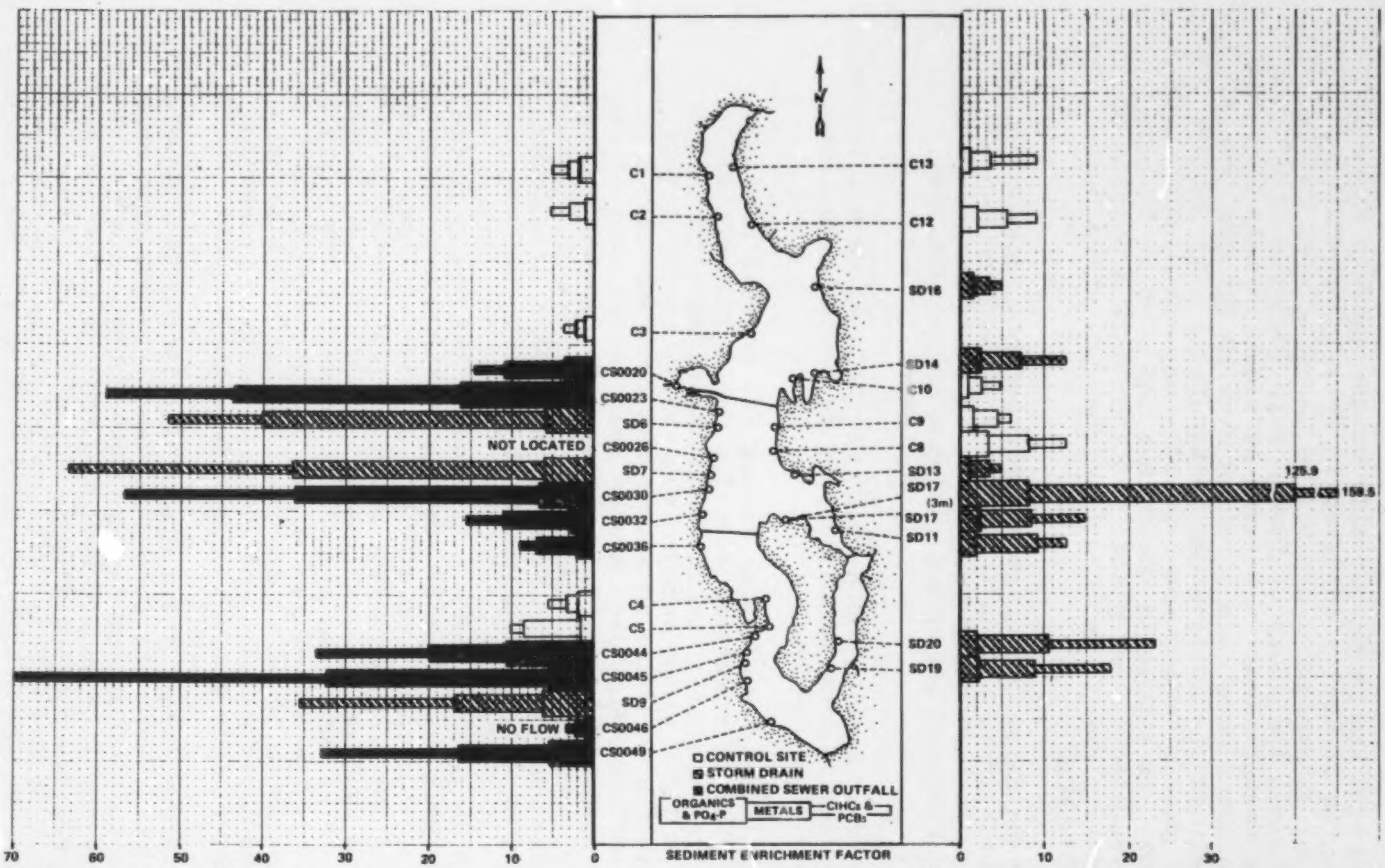


Figure 8. Relative enrichment of the nearshore surface sediments of Lake Washington with normalized categories of parameters (refer to text for details of data reduction). Organics and PO_4-P: total organic carbon, oils and greases, total phosphorus; metals: copper, lead, zinc, mercury; chlorinated hydrocarbons and PCBs: BHC, lindane, Heptachlor, Heptachlor E, Aldrin, Dieldrin, Endrin, DDT (DDD + DDE + o,p DDT + p,p DDT), Arochlor 1242, Arochlor 1248, Arochlor 1254, Arochlor 1260.

Sediments around the sewer outfalls on the eastern shore of Lake Washington generally appeared to be only one-third to one-fourth as contaminated overall as those between the two floating bridges and south of Seward Park (denoted by C 4 and C 5) on the western shore. Several stations in this area had sediment enriched more than 16 times over background levels. The area between the bridges had particularly high concentrations of metals, which are typically associated with both CSOs and SDs. It should be noted that the pipe at Station SD 6 has separated in two places and that only a portion of the wastewater plume is emitted from the end, where the samples were taken.

On the western shore, chlorinated hydrocarbons (predominantly DDT) were widespread and up to 37 times background concentrations. PCBs were found only at Stations SD 11 and SD 13 in concentrations of 118.6 and 49.8 ppb dry weight, repectively.

The sediments in the northern third of the lake were relatively clean, with the maximum enrichment being about three times background.

The storm drains around Mercer Island had created some problems. Sediments sampled at a 3 m depth just off SD 17 (SD 17-3 m) were over twice as contaminated with metals and DDT (75 times background levels) as any others found in the lake. These sediments had been enriched by particulates from a drainage system that serves most of the Mercer Island business district. They were rapidly filling in the portion of the bay around the outlet channel; aerial photos of the area taken on February 6, 1978 show a large surface film of oil or gasoline there.

Analyses of sediment samples collected at the mouth of the drainage channel (SD 17) indicate that most of the contaminants were swept a little further offshore before settling. These observations are in accord with dye circulation studies done at this site by CH2M/Hill (1973), who found the circulation in the bay to be dominated by a large eddy--a pattern which would tend to promote sedimentation. Unfortunately, the shoaling was found to be so extensive that the sediments were stirred by propellers and boat hulls, thus precluding more intensive study as part of the present project.

Two other Mercer Island storm drains--SD 19 and SD 20--were also associated with sediments that were higher in DDT than those at any site sampled on the eastern lake shore. Storm Drain 19, which enters the lake at the northern edge of a large public swimming area, was subsequently selected for more intensive study. SD 20 drains a large area (> 200 acres) in the center of the island and runs into the lake next to a private dock.

Over a ten-year period it has built up a sediment delta next to the dock that extends approximately 20 m into the lake. As a result the landowner has been obliged to build a second pier for boat moorage. It should be noted that the metals contamination of these sediments was also found to be equivalent to or greater than at any station sampled on the eastern shore.

In order to define the nature and strength of any relationships that might exist among the various sediment parameters, correlation matrices were calculated for the data grouped by station type (CSOs, SDs, controls). The results are presented in Tables 1-3. The square of the correlation coefficient for any two parameters indicates that fraction of the total variation in the dependent variable Y that is explained by fitted regression; confidence levels have been denoted in the tables for the most significant correlations.

It is apparent that the greatest number of significant correlations was found for the SD sediment parameters. In this sense the CSO sediments were only slightly less diverse than the control sediments, which is surprising considering the partial stormwater content of the CSO effluents. The most closely correlated parameters were: Cu/Zn (SD), r = .888; Cu/Zn (CSO), r = .887; Pb/O&G (SD), r = .870; Cu/Zn (control), r = .841; TOC/O&G (CSO), r = .835; TOC/ClHC (SD), r = .821; Zn/TPO_4 (CSO), r = .809; Hg/ClHC (SD), r = .768; and O&G/ClHC (SD), r = .767.

Thus, it may be seen that Cu and Zn were strongly related in all sediments studied in the lake, indicating common source(s) and possibly extensive longshore circulation. Recent studies done by Metro (unpublished data) have shown the primary source of these two metals in Seattle's combined sewers to be domestic plumbing; their origin in storm drainage is less well defined. The strong relationship between Pb and O&G in the storm drain sediments was not unexpected, motor vehicles being the prevalent source of both; this relationship was also present (but weaker) in the CSO sediments. TOC and O&G also had multiple significant correlations with other parameters at the CSO and SD stations.

It is of interest to note that chlorinated hydrocarbons (ClHCs) were significantly correlated with various other parameters measured in SD sediments (TOC, Hg, O&G, Pb and Zn), whereas CSO sediments showed virtually no evidence of such relationships. This would seem to indicate that the ClHCs enter the combined sewer wastes predominantly in the storm water fraction, a supposition that is commensurate with the fact that the primary component of the ClHC values was DDT, which until recent years was a widely-used pesticide.

TABLE 1. CORRELATION MATRIX FOR COMBINED SEWER SEDIMENTS.

	Cu	Hg	Pb	Zn	TOC	O & G	ClHC	TPO_4
Al	-.330 (10)	-.345 (10)	.185 (10)	-.324 (10)	-.529 (9)	-.357 (9)		-.279 (10)
Cu		.255 (18)	-.051 (18)	.887**(18)	-.088 (17)	.115 (16)	.239 (8)	.588**(18)
Hg			.022 (18)	.414*(18)	-.029 (18)	.123 (17)	.426 (9)	.439*(18)
Pb				.014 (18)	.224 (17)	.491*(16)	.184 (8)	.014 (18)
Zn					-.152 (17)	.093 (16)	.106 (8)	.809**(18)
TOC						.835**(16)	.515 (9)	-.022 (17)
O & G							.592 (8)	.207 (16)
ClHC								.609 (8)

* 95% confidence level.
** 99% confidence level.
() Number of samples.

TABLE 2. CORRELATION MATRIX FOR STORM DRAIN SEDIMENTS

	Cu	Hg	Pb	Zn	TOC	O & G	ClHC	TPO_4
Al	.326 (13)	-.347 (11)	-.070 (13)	.100 (13)	-.270 (11)	.061 (12)		.253 (13)
Cu		.211 (21)	.478*(23)	.888**(23)	.327 (21)	.561**(22)	.519 (10)	.497**(23)
Hg			.069 (21)	.239 (21)	.545**(21)	.292 (21)	.768**(10)	.514**(21)
Pb				.481*(23)	.167 (21)	.870**(22)	.688*(10)	.039 (23)
Zn					.162 (21)	.549**(22)	.602*(10)	.355 (23)
TOC						.217 (22)	.821**(11)	.584**(22)
O & G							.767**(11)	.245 (23)
ClHC								.539*(11)

* 95% confidence level.
** 99% confidence level.
() Number of samples.

TABLE 3. CORRELATION MATRIX FOR CONTROL SEDIMENTS

	Cu	Hg	Pb	Zn	TOC	O & G	ClHC	TPO_4
Al	.273 (10)	.418 (10)	.223 (10)	.639*(10)	.400 (10)	-.087 (10)		.416 (10)
Cu		-.024 (19)	.299 (21)	-.841**(21)	.279 (19)	.243 (20)	-.036 (9)	.521**(21)
Hg			.391*(19)	.146 (19)	-.280 (20)	-.280 (20)	.157 (10)	.574**(19)
Pb				.123 (21)	.086 (19)	.173 (20)	.436 (9)	.429*(21)
Zn					.154 (19)	.137 (20)	-.050 (9)	.478*(21)
TOC						.035 (20)	.186 (10)	-.259 (19)
O & G							.244 (10)	-.051 (20)
ClHC								-.096 (9)

* 95% confidence level.
** 99% confidence level.
() Number of samples.

Intensive Studies

Discharge Monitoring --
Discharge Loading Estimates for Single Events -- The combined sewer overflows and storm drainage generated by several storms were sampled quantitatively and qualitatively at CSO 023 and SD 7 in order to determine typical particulate inputs to the freshwater environment by a representative CSO and SD. These systems were selected in preference to CSO 044 and SD 19 because they were easier to sample. Table 4 is a summary of the storms monitored.

TABLE 4. SUMMARY OF RAINSTORMS MONITORED FOR QUANTITY AND QUALITY OF DISCHARGES INTO LAKE WASHINGTON FROM COMBINED SEWER OUTFALL 023 AND STORM DRAIN 7, MARCH-SEPTEMBER, 1978

Date	Station	Total Rainfall (cm)	Overflow Duration (hr)	Discharge Volume (m^3)	Discharge Fraction(a) (%)
3/6 - 3/7	SD 7	1.75	23	1001	10.8
3/23	CSO 023	0.43	2	53	2.5
	SD 7	0.43	5	213	9.3
3/24 - 3/25	CSO 023	0.74	23	51	1.3
	SD 7	0.74	29	835	20.8
4/15 - 4/16	CSO 023	2.67	20.5	951	7.4
	SD 7	2.67	21	1849	13.4
8/31 - 9/2	CSO 023	2.11	38.5	663	6.7
	SD 7	2.11	32.5	567	4.4

(a) The fraction of the total basin-incident rainfall that was discharged by the outfall during the period noted.

For the Seattle region the months represented include the end of the rainy season and most of the dry season. Because the drainage basins for the two stations sampled were only 2.4 km apart, with similar orientation and no intervening ridges, a single rain gauge was used for both.

The similarities in relative size of the CSO 023 and SD 7 drainage basins and incident rainfall for any given storm invited comparisons of their pollutant loading and runoff characteristics.

The major distinction affecting the relative quality of runoff for these two areas was land-use distribution; the CSO 023 basin was comprised of approximately 75% single family residences, with the rest multiple family residences, whereas the SD 7 basin had an estimated 90-95% of its area devoted to single family residences (normally associated with lower pollutant accumulation rates than multiple family residences). For three of four storms an appreciably lower percentage of the total rainfall on its drainage basin was discharged by CSO 023 than by SD 7; this was to be expected, since a CSO discharge is typically intermittent, whereas that of an SD is continuous. On the other hand, the relative magnitudes of the mean storm discharge concentrations for the various pollutants varied from one storm to the next, as will be discussed below. A statistical summary of the contaminant mass discharges is offered in Table 5.

Mean ratios (SD 7: CSO 023) of per-storm mean concentrations and total loadings are also presented here for each parameter, in support of the ensuing discussion (Table 6). Whereas the data from four storms were available for calculation of the values given in Table 6, those from only two storms were so used. The annual cycle of SD 7: CSO 023 ratios of per-storm discharge volumes indicated that the SD is disproportionately affected by groundwater inputs during the wet season; therefore it was decided to eliminate two of the three wet season storms to reduce the bias in the calculation of annual mean pollutant concentrations. Mercury, aluminum and organic carbon data were not available for both of the storms used and consequently no annual means were calculated for these parameters.

Particulate Discharge -- With reference to Table 6, the SD 7: CSO 023 ratios of mean particulate concentrations were appreciably less than 1.0 for suspended solids, Cu, Zn, total P, and chlorinated HC. Only Pb had a significantly higher solids concentration at SD 7, this at least partially due to dilution by low-lead sanitary wastes at the CSO. However, the mean discharge volume for SD 7 was 1.5 times that of CSO 023, and consequently the mean storm particulate loadings for suspended solids, Pb, and Zn at SD 7 were greater than those at CSO 023. The mean loading values for ClHC were similar for the two sites, giving a SD:CSO ratio near 1.0.

For the three storms monitored at both stations (Table 5), there were consistently higher mass loadings of Al from SD 7 than from CSO 023, indicating a greater input of inorganic terrigenous materials to the lake by the storm drain. The percentage of the total Al found to be associated with particulate matter was high, invariate and nearly identical (approximately 96%) for the two outfall sites, implying that Al was present in the overflows predominantly as the relatively insoluble aluminosilicates, i.e., inorganic terrigenous material. As such it was used as an inorganics tracer in the subsequent water column and sediments

TABLE 5. SUMMARY OF ESTIMATED TOTAL POLLUTANT LOADS AND FRACTION OF PARTICULATES IN STORM DISCHARGES MONITORED AT COMBINED SEWER OUTFALL 023 AND STORM DRAIN 7, MARCH-SEPTEMBER, 1978

	CSO 023		SD 7	
MASS RANGE:	kg	No. of Storms	kg	No. of Storms
Suspended Solids	6.40 - 142	4	27.4 - 142	5
Total Cu	.001 - .039	4	.020 - .049	5
Total Hg	.0000 - .0008	4	.0000(a) .0004	5
Total Pb	.001 - .041	4	.098 - .316	5
Total Zn	.003 - .113	4	.044 - .156	5
Total Al	.059 - 2.56	3	.762 - 6.62	4
Total Organic C	.865 - 18.0	2	11.0 - 16.2	2
Total TPO_4-P	.059 - 1.28	4	.120 - .417	4
Total O & G	.584 - 9.41	4	.740 - 8.06	5
Particulate ClHC(b)	.316 - 100 mg	4	1.02 - 86.1	5
MEAN PARTICULATE MASS:	Percent(c) of Total Mass	No. of Storms	Percent(c) of Total Mass	No. of Storms
Suspended Solids	100.0	4	100.0	5
Cu	78.1 ± 10.2	4	64.0 ± 8.7	5
Hg	88.4 ± 6.9	2	ND(a)	5
Pb	69.1 ± 14.2	4	88.1 ± 2.7	5
Zn	68.6 ± 19.6	4	64.1 ± 5.0	5
Al	96.0 ± 2.0	3	96.6 ± 0.9	4
Organic C	42.1 ± 22.9	2	56.0 ± 8.1	2
TPO_4-P	28.5 ± 10.3	4	52.7 ± 13.1	4
O & G	NA(d)		NA	
ClHC	ND(e)		ND	

(a) Below detection limits.

(b) Selected chlorinated hydrocarbons: α-BHC, lindane, heptachlor, heptachlor E, aldrin, dieldrin, endrin and DDT (DDD + DDE + o,p DDT + p,p DDT).

(c) $\bar{x} \pm 1\sigma$.

(d) Not applicable.

(e) Not determined.

TABLE 6. INTERSTATION COMPARISON FOR STORM DRAIN 7 AND COMBINED SEWER OUTFALL 023 OF MEAN DISCHARGE CONCENTRATIONS AND POLLUTANT LOADINGS ESTIMATED FOR TWO STORMS[a] MONITORED AT BOTH SITES

	Mean Concentration (mg/l)			Mean Discharge Load (kg)		
Parameter	SD	CSO	SD:CSO	SD	CSO	SD:CSO
Suspended Solids	94.4	126	0.7	114	102	1.1
Total[b] Cu	.030	.048	0.6	.036	.039	0.9
Particulate Cu	.018	.035	0.5	.022	.028	0.8
Total Hg	ND[c]	.0006	ND	ND	.0005	ND
Particulate Hg	ND	ND	ND	ND	ND	ND
Total Pb	.171	.046	3.7	.207	.037	5.6
Particulate Pb	.155	.030	5.2	.187	.024	7.8
Total Zn	.083	.108	0.8	.100	.087	1.1
Particulate Zn	.054	.067	0.8	.065	.054	1.2
Total TPO$_4$-P	.266	1.47	0.2	.321	1.19	0.3
Particulate TPO$_4$-P	.170	.418	0.4	.205	.337	0.6
Total O & G	4.33	8.85	0.5	5.23	7.14	0.7
Particulate ClHC[d]	.038 ug/l	.052 ug/l	0.7	45.8 mg	51.6 mg	0.9

(a) Storms of 4/15/78 and 8/31/78. The ratio of mean discharge volumes for SD:CSO was 1208 m^3:807 m^3 = 1.5.

(b) Soluble + particulate.

(c) Not determined (below detection limits).

(d) Selected chlorinated hydrocarbons: α-BHC, lindane, heptachlor, heptachlor E, aldrin, dieldrin, endrin and DDT (DDD + DDE + o,p DDT + p,p DDT).

studies.

There was a large variation from one storm to the next in the mean concentrations and total mass loading of chlorinated hydrocarbons at both sites (Table 5). Trends at the two stations were similar in that DDT accounted for a very large portion (approximately 75-95%) of the total loading of particulate pesticides during the spring storms, and only about half of the August-September storm total, which was itself appreciably lower than that of the other storms. Lindane was the only other pesticide consistently present at both stations. The persistent occurrence of DDT and lindane conforms to the observations of Brenner et al. (1978) for runoff from the Juanita Creek watershed in the northeastern segment of the Lake Washington basin. The occurrence of these contaminants in both the CSO and SD systems indicates that they were present in the storm drainage, rather than in the sanitary wastes. Low concentrations of two other pesticides, benzene hexachloride (BHC) and aldrin, were also detected in the fall storm discharges; lindane, BHC and aldrin levels in the sediments were comparable at the two stations.

Total Discharge -- With two exceptions, the SD:CSO ratios calculated for mean pollutant concentrations in the unfiltered (total) storm discharges were similar to those estimated for the particulate fractions alone. The ratios for Pb and TPO_4-P in the total discharges were notably lower, indicating that in comparison to the CSO analysis, an appreciably larger fraction of the Pb and TPO_4-P in the SD discharges was determined to be particulate. This observation agrees with the data presented in Table 5 for the larger storm set, values which include the above-mentioned wet weather bias.

Viruses -- The results of virus analyses performed on CSO 023 and SD 7 discharges are summarized in Table 7. As evidenced by these data, it seems unlikely that there are any human viruses present in typical storm drain discharge. This finding is logical in view of the expected absence of human fecal wastes in storm drainage. With rare exceptions, human viruses only infect, and are excreted by, humans. Therefore, their presence in a storm water system would be indicative of its contamination by human fecal wastes from leaking sanitary sewers, septic tanks or landfill runoff. Whereas these conditions do occasionally occur, they represent deviations from the norm.

On the other hand, viruses were readily detected in the discharges of CSO 023. From the substantial difference in the two estimates made for that system, one is led to consider those factors which may characteristically influence the virus levels of combined wastewater. Generally, the virus concentrations are a function of the concentrations of fecal matter in the municipal wastewater; this in turn is dependent upon two variables--rate of input and dilution within the system.

TABLE 7. SUMMARY OF VIRUS ANALYSES OF DISCHARGES FROM COMBINED SEWER OUTFALL 023 AND STORM DRAIN 7

Station	Date	Total Overflow Vol. (m^3)	No. Viruses/m^3	Recovery Efficiency (%)
CSO 023	7/16/78	454	1.32×10^6	2.1
	10/23/78	625	0.21×10^6	3.4
SD 7	9/22/78	2120	0	9.4
	11/08/78	16	0	1.1

The rate of input of fecal wastes typically varies with time of day. If an overflow occurs at a time of day when toilets are heavily used, the result will be a correspondingly high concentration of feces (and therefore viruses) in the combined discharge. Flow data from Seattle Metro's wastewater treatment plants indicate two principal peaks during rainless days, one occurring at about 6-11 a.m., and the other at about 4-8 p.m. With reference to Table 7, the sample with an estimated 1.32×10^6 viruses/m^3 was pumped from the CSO 023 system at 10 a.m., during the period of highest morning inputs. The sample containing 0.21×10^6 viruses was collected at 11 p.m., well after the evening peak.

The other principal factor influencing virus concentrations is dilution within the sewer system. During an intense rain the proportion of storm water in the combined sewage would be greater than during a lighter storm. Thus, given equal fecal loading to the system, virus concentrations might be expected to be higher during the latter event. It is important to note, however, that the total virus loading to the receiving waters is basically a function of total overflow volume, and in this sense the dilution effect of a more intense storm tends to be compensated by a correspondingly greater discharge volume. Consequently, the most influential factor regarding virus loading is probably the time of day at which an overflow occurs.

Rainfall, Flow and Loading Summary -- The total Seattle rainfall for the March, 1978 - February, 1979 study period was near the annual average. The rainfall at the Denny Way combined sewer outfall totalled 98.8 cm (38.9 in), whereas a 30-yr mean measured for a site just 2.7 km to the SE and at a similar elevation (Phillips, 1968) was 86.6 cm (34.1 in). The 1978 spring and summer were somewhat wetter than usual, but the 1978-1979 winter was drier, compensating for most of the observed difference.

The rainfall records for the CSO 023 - SD 7 - CSO 044 study area show a substantial variance with the aforementioned totals for the downtown area. The total rainfall recorded for this portion of the western shore of Lake Washington was 58.9 cm (23.2 in), a value confirmed by three separate gauges (near CSO 020, SD 7 and CSO 046 in Figure 2). It seems probable that this annual difference of 28 cm of rain represents a shielding effect, or rain-shadow, with the hills of the city blocking part of the precipitation from the storm fronts, which typically come from the southwest.

The protected areas on the northeast sides of the region's hills are apparently quite restricted - a gauge located approximately 1.3 km east of Mercer Island's easternmost promitory collected 90.0 cm (35.8 in) of rain during the study period, indicating very little protection from the island's 90-120 m hills. No rainfall data were collected for SD 19, but on the basis of its location on the eastern side of Mercer Island, it seems likely that the total for the one year study period was less than the 90.9 cm (35.8 in) recorded across the channel.

The overflow response to the indicated rainfall pattern is shown in Figure 9. The values given for SD 7 represent flow above baseline. For a total of 62 periods of measurable rainfall (separated by one or more dry days), there were 48 overflows at each of the two stations, CSO 023 and SD 7. Taking into account the fact that multiple overflows occurred during some of the long storms, the fraction of those storms resulting in increased discharge at one or both stations was 76%; the average total rainfall for those storms that failed to generate increased discharge was 0.1 cm (.04 in).

The total discharge volumes for the 12-month monitoring period were: CSO 023 - 25,600 m^3 (6.76 MG); SD 7 - 27,700 m^3 (7.34 MG), + 50,200 m^3 (13.3 MG) base flow. In combination with the mean discharge concentrations given in Table 5 and with concentrations measured for non-storm discharge at SD 7, these values were used to calculate total annual loads for the various parameters of interest. The results are presented in Table 8.

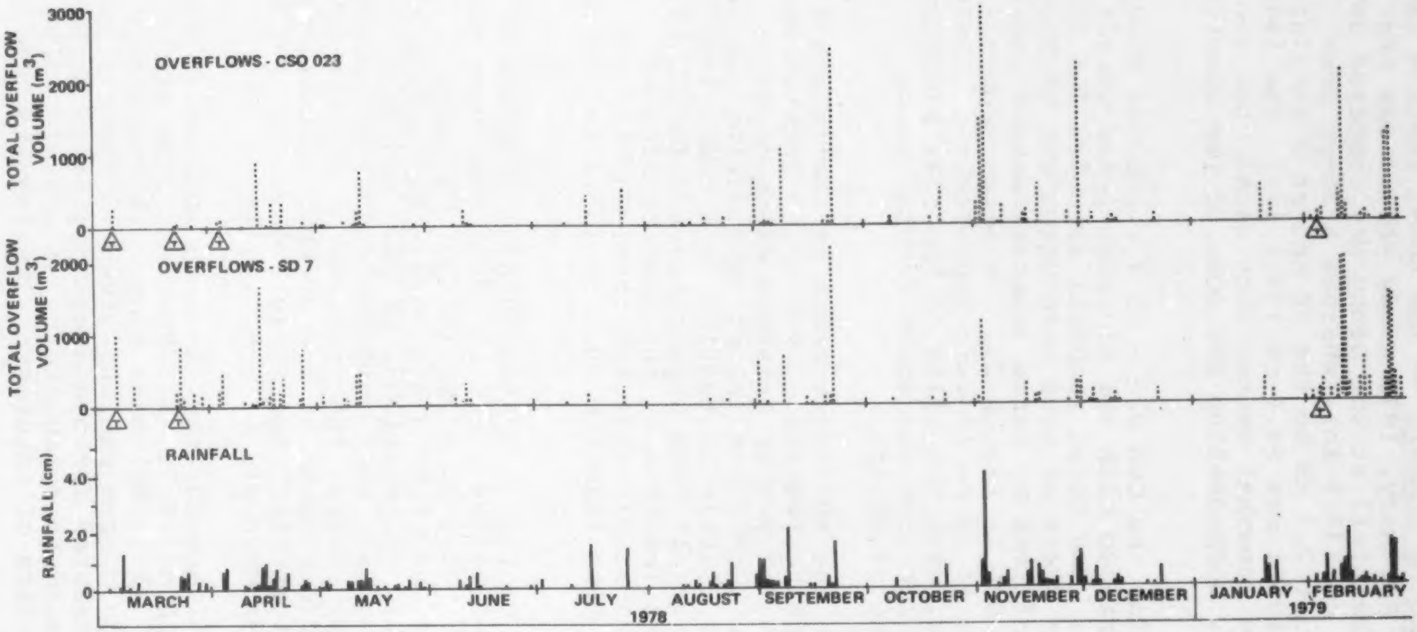


Figure 9. Summary of rainfall and overflow response at Combined Sewer Outfall 023 and Storm Drain 7 from March 1978 to February 1979. The triangle symbols designate storms monitored for discharge turbidity distributions.

TABLE 8. ESTIMATED(a) TOTAL ANNUAL MASSES OF SELECTED CONSTITUENTS IN DISCHARGES FROM COMBINED SEWER OUTFALL 023 AND STORM DRAIN 7-- MARCH 3, 1978 TO FEBRUARY 28, 1979

	CSO 023	SD 7		
Parameter	Storm (Total) (kg)	Storm (kg)	Non-Storm (kg)	Total (kg)
Suspended Solids	3230	2610	666	3280
Total(b) Cu	1.23	.831	.904	1.74
Particulate Cu	.896	.499	.663	1.16
Total Pb	1.18	4.74	1.00	5.74
Particulate Pb	.768	4.29	.502	4.79
Total Zn	2.76	2.30	.502	2.80
Particulate Zn	1.72	1.50	.050	1.55
Total TPO_4-P	37.6	7.37	5.27	12.6
Particulate TPO_4-P	10.7	4.71	.502	5.21
O & G	227	120	65.3	185
Particulate ClHC(c)	1.33g	1.05g	.150g	1.20g

(a) See text for details of estimate derivations.
(b) Soluble + particulate.
(c) Selected chlorinated hydrocarbons: α-BHC, lindane, heptachlor, heptachlor E, aldrin, dieldrin, endrin and DDT (DDD + DDE + o,p DDT + p,p DDT).

For all constituents except Pb, the annual storm loading of particulates was less from the storm drain than from the combined sewer. However, with the non-storm loading of the storm drain added to its storm inputs, the totals for suspended solids and Cu also exceeded those of the combined system. The parameter relationships were similar for the total (particulate + soluble) loading, except that the total Zn loading from the two systems was essentially equal. The annual mass of Cu, Pb, Zn and TPO_4-P discharged by the CSO were all 60-65% particulate; the relative values at the SD varied considerably being 67%, 83%, 55%, and 41%, respectively.

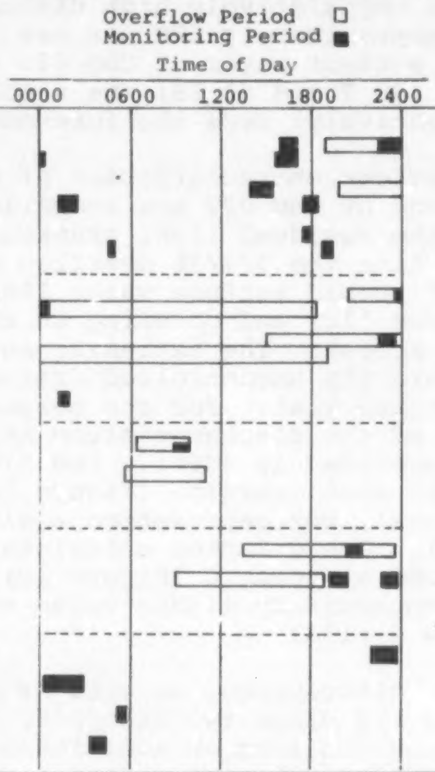
The difference in the percentage of particulate P estimated for the two stations is undoubtedly due to the presence of high-P sewage particulates in the combined system. The relative difference recorded for Pb, however, implies the influence of some process in addition to dilution by low-Pb municipal wastes in the CSO. The presence of an unidentified source of high-Pb particulates in the SD drainage basin seems unlikely. A more reasonable conjecture is that a large fraction of the comparatively heavy, Pb-bearing particulates bypasses the overflow barrier in the CSO system; by contrast, no such bypass exists in the SD, so that a greater portion of the heavy particulates are routinely discharged.

The total mass of solids discharged by the two outfalls during the one year study period was 3.2 metric tons by CSO 023 and 3.3 metric tons by SD 7. Based on the respective settling rates of .752 and .805 $g/m^2/day$ measured by the sediment traps, a uniform blanket of this material would cover 1.4 hectares (3.5 acres) at CSO 023 and 1.0 hectares (2.4 acres) at SD 7. However, the biologically-affected area around CSO 023 (based on oligochaete counts) was determined to average 0.6 hectares (1.4 acres) for the two seasons sampled, indicating that more than 60% of the solid material was rapidly transported away from the outfall. This fraction would be appreciably larger at SD 7; in fact, so much of the solid material moved away from the outfall and out of the sample grids that a comparable estimate for the storm drain was not feasible. Such estimates are, of course, very rough due to the extreme variability of settling dynamics as functions of distance and direction from an outfall.

Receiving Water Monitoring --

Turbidity Distributions of Discharge Plumes -- The distributions and movements of discharge plumes was monitored at CSOs 023 and 044 and SDs 7 and 19 during a number of storms, as summarized in Table 9. These measurements were made using a submersible light transmissometer system of the type originally described by Petzold and Austin (1968). This instrument provides a measurement of the volume attenuation coefficient, α, which is equivalent to the sum of the light scattering and absorption coefficients. The volume attenuation coefficient may in turn be related to common turbidity units using methods described by Austin (1973), who determined the relationship between α and Jackson Turbidity Units (JTU) to be approximately linear for natural water of moderate to good clarity.

TABLE 9. SUMMARY OF FIELD TRIPS FOR MEASURING TURBIDITY DISTRIBUTIONS OF DISCHARGE PLUMES



Date	Station	Overflow Volume (m^3)	Rainfall (cm)
3/6/78 - 3/7/78	CSO 023	303	1.75
	SD 7	1130	1.75
	C3	NA(a)	1.75
3/24/78 - 3/25/78	CSO 023	56	1.02
	SD 7	711	1.02
	C 3	NA	1.02
4/4/78	CSO 023	62	.46
	SD 7	201	.46
2/6/79	CSO 023	156	.99
	SD 7	299	.99
2/11/79	CSO 044	ND(b)	2.13(c)
2/12/79	SD 19	ND	2.21(c)
	C 3	ND	3.15(c)
	C 4	ND	2.36(c)

(a) Not applicable.
(b) Not determined.
(c) Rainfall up to and including period of monitoring.
The other values given cover the entire overflow period.

For the purpose of plume tracing, the light transmission (turbidity) data were reduced to sectional contour plots. These included aerial perspectives at various depths, and onshore-offshore and longshore transects showing light transmission patterns from the perspective of a diver looking across the lake bottom. Representative plots were selected for presentation here to show observed trends of particulates movement. In addition to data from the four outfall areas, the results of storm measurements from the two control sites (C 3 and C 4) are also included.

Contrary to intentions, we were unable to obtain light transmission data for periods of lake stratification. The data presented here were collected during March and April of 1978 and February of 1979 and in all instances show the discharge plumes to have been intersecting the surface. At the two combined sewer outfall sites (CSO 023 and CSO 044) this was due predominantly to the comparatively high discharge temperatures, e.g., a difference of approximately 6°C was measured for a comparison of discharge and ambient water at CSO 023 on 4/4/78. For the two storm drains (SD 7 and SD 19) the shallow discharge depths (2 and 0 m, respectively) were the foremost determinants.

CSO 023 -- The various characteristics of the discharge plume dispersion observed at CSO 023 are summarized in Figures 10-14. Figure 10 shows the residual light transmission distributions 21.5 hr from the time the 3/7/78 overflow began. The plume was seen as a lens of turbid surface water 150 m NE of the outfall, 2.7 m thick (Figure 11c) and covering an area of approximately 4.5 hectares (11 acres). The extremely muddy water SW of the outfall was temporarily uncontrolled drainage from a nearby building site (Figure 11a). For the measured CSO discharge of 303 m^3, the size of the discharge plume at that time represented a dilution of approximately 400:1. The plume of 4/4/78, measured 3 hr into that overflow (Figure 12), covered only 0.6 hectares (1.5 acres), but represented a similar estimated dilution of 615:1. The dilution calculated for a lens of turbid surface water found at point C (Figure 10) on 3/24/78 - 3/25/78, however, had an appreciably higher value - 2000:1 - only 3.5 hr into the overflow period.

This considerable discrepancy, in view of the comparatively good agreement between the other two examples, implies an unaccounted-for volume contribution from an additional source: the large, nearshore storm drain indicated in the figure. Interference from that system was much more obvious during the storm of 2/6/79 (Figure 13); a contour plot of an onshore-offshore transect in that location (Figure 14) clearly indicates a tongue of turbid wastewater moving offshore from the drain site. The location of the 156 m^3 of discharge known to have been released by CSO 023 was obscured by the storm drainage.

The surface position of a discharge lens as a function of time gives an incomplete indication of particulate circulation patterns. Much of the solid material present in

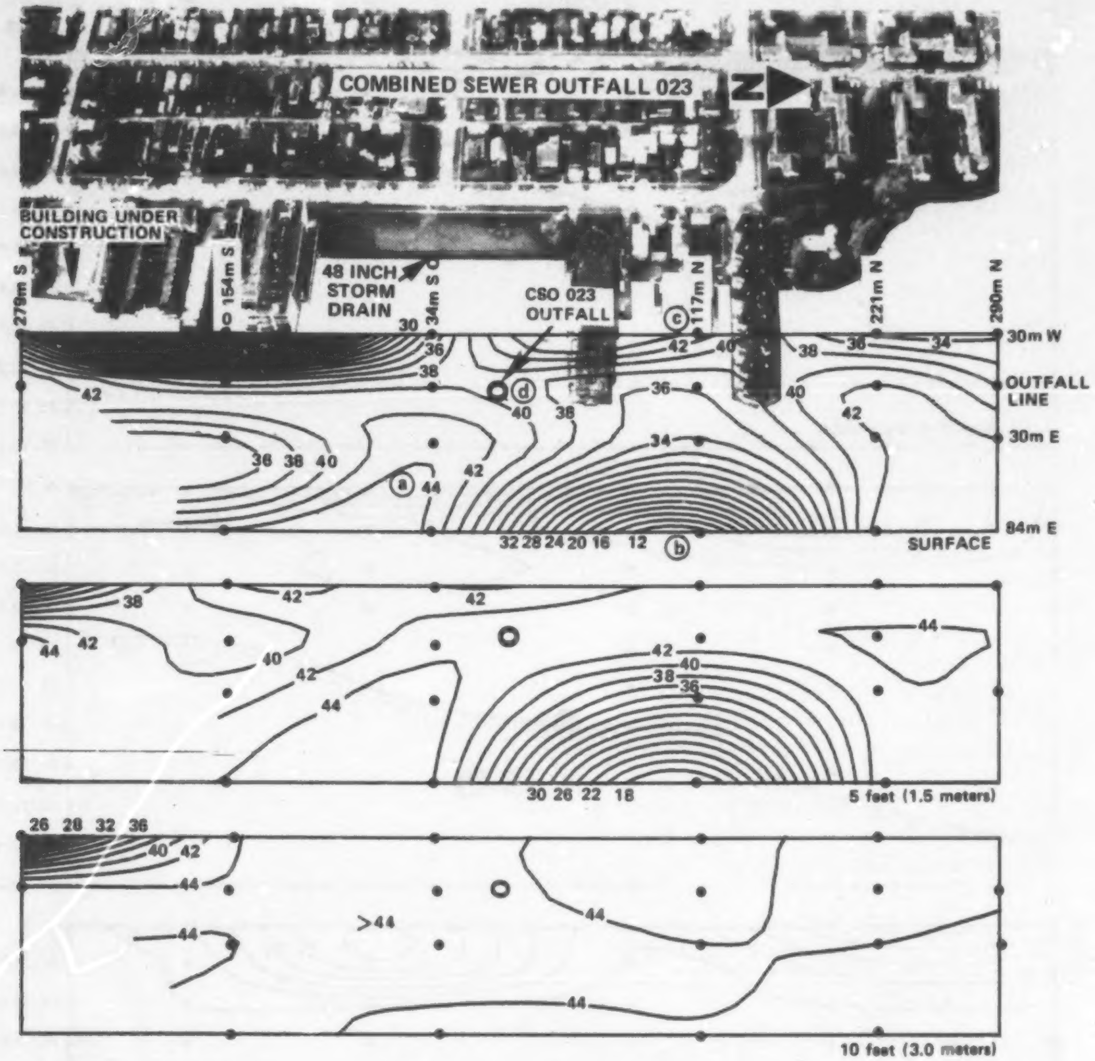

COMBINED SEWER OUTFALL 023
N
BUILDING UNDER CONSTRUCTION
48 INCH STORM DRAIN
CSO 023 OUTFALL
279m S
154m S
34m S
117m N
221m N
290m N
30m W
OUTFALL LINE
30m E
84m E
SURFACE
a
b
c
d
32 28 24 20 16 12
5 feet (1.5 meters)
30 26 22 18
26 28 32 36
>44
10 feet (3.0 meters)

Figure 10. Aerial perspectives of contours of percent light transmission at Combined Sewer Outfall 023--1533-1645 hrs., 3/7/78. The lettered symbols indicate surface positions of the discharge plume core at time of overflow initiation plus (a) 5 hr, 3/6/78; (b) 21.5 hr, 3/7/78 (distribution shown); (c) 3.5 hr, 3/24/78-3/25/78; and (d) 3 hr, 4/4/78.

these features apparently remains suspended for extended periods of time, as evidenced by the high light transmission (lack of turbidity) at mid-depths in Figure 11, and is ultimately advected out of the area. However, Figures 12 and 13 indicate that a substantial local fallout and settling of

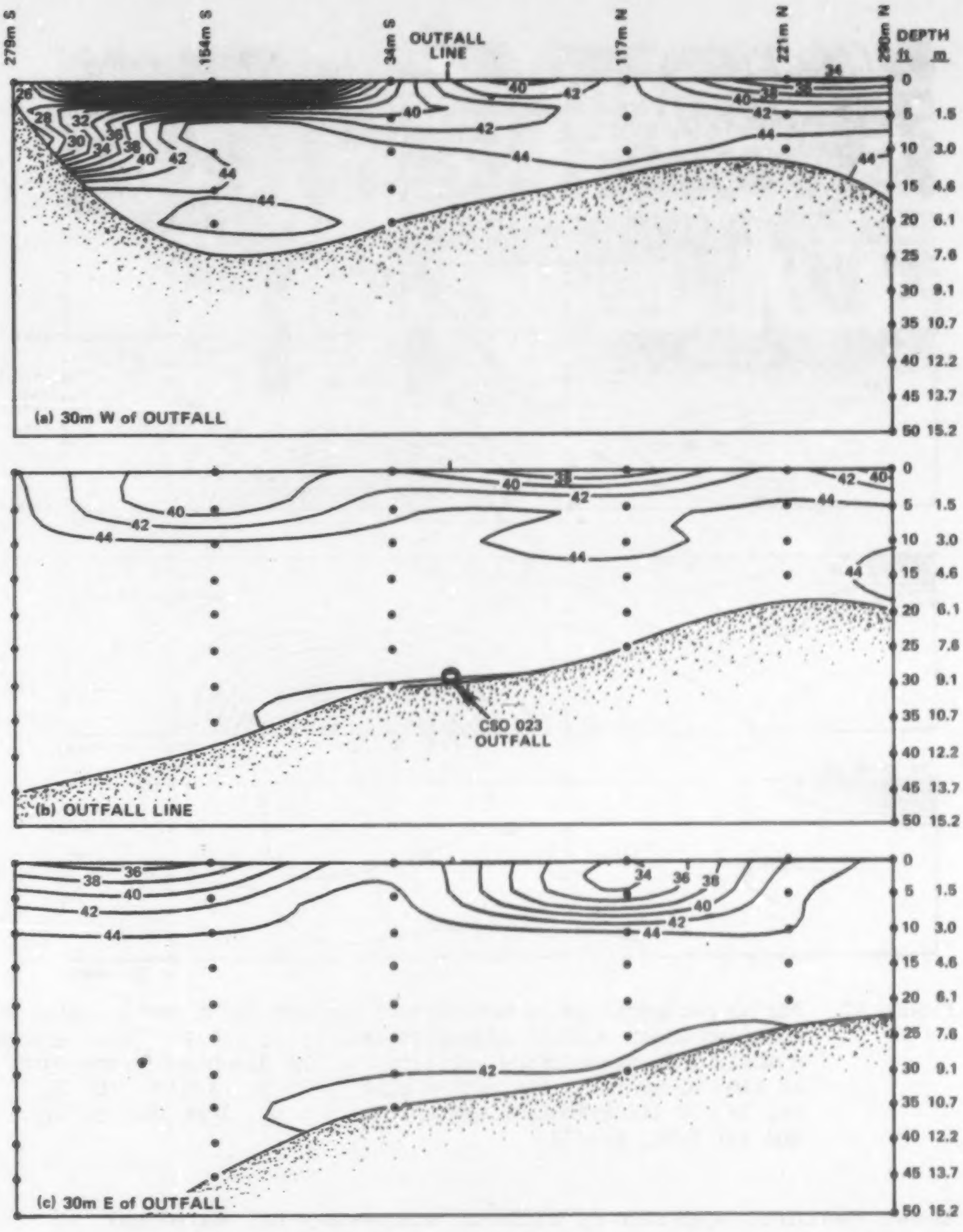


Figure 11. Longitudinal sections of contours of percent light transmission at Combined Sewer Outfall 023--1533-1645 hrs., 3/7/78. The perspective is that of a diver facing shore.

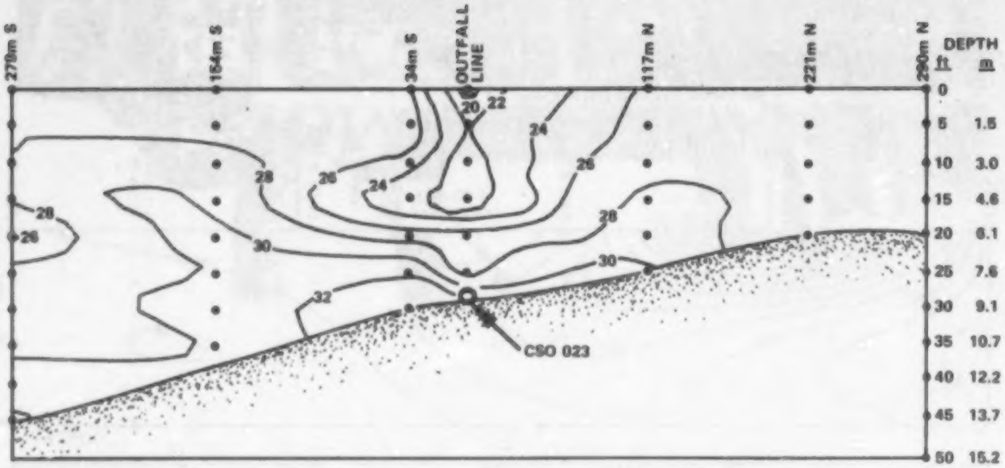


Figure 12. Longitudinal section through the Combined Sewer 023 outfall, showing contours of percent light transmission--0856-0954 hrs., 4/4/78. The perspective is that of a diver facing the shore.

particulates occurs in the outfall area during the overflow. The settling pattern denoted by Figure 13 indicates a downslope movement of materials near the bottom (refer to Figure 3 for CSO 023 bathymetry). The observed combination of suspended transport and downslope settling was also quite evident at SD 7 and SD 19, as described below. These observations correlate well with the measured distributions of sediment surface contaminants presented elsewhere in this report.

SD 7-- Considerable discharge interference was also observed in the light transmission distributions measured for storm discharges at SD 7. Substantial inputs from a 60 cm storm drain 345 m north of the SD 7 outfall were recorded for the storm of 2/6/79. The relevant areas of influence for the two outfalls are strikingly apparent in Figures 15 and 16, which give aerial light transmission distributions at one and four hours elapsed time following a 10-hour storm discharge at SD 7. During the three-hour interim period, the SD 7 plume began to dissipate, and the pattern of discharge from the other outfall became more prevalent. The small cove between the two outfalls appears to have encouraged a local eddy in the nearshore circulation, resulting in a southerly movement of discharge offshore. There were also manifestations of this clockwise circulation pattern, and of particulates expelled by the second storm drain, in storm data collected 3/6/78 - 3/7/78.

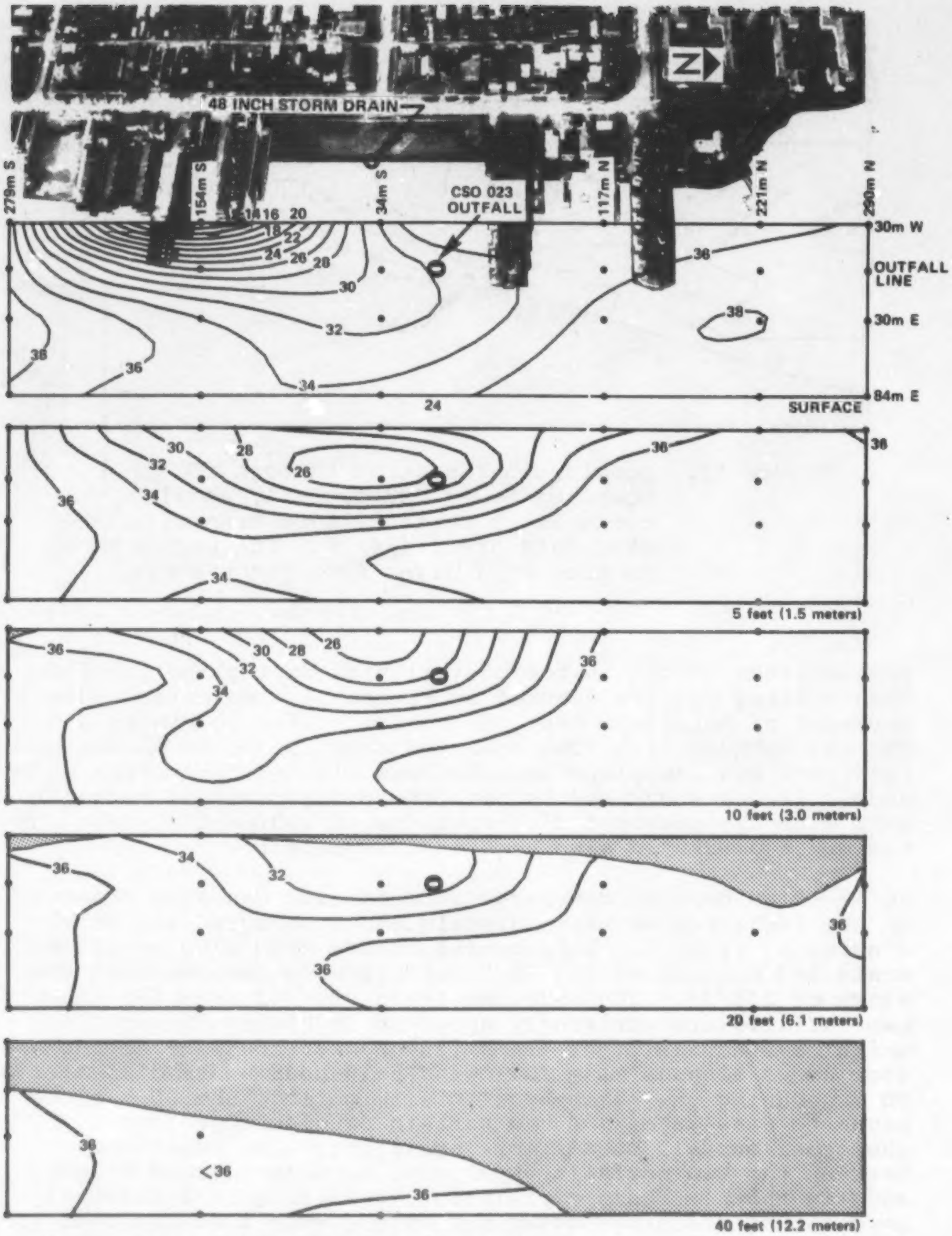

48 INCH STORM DRAIN
N
279m S
154m S
34m S
117m N
221m N
290m N
CSO 023 OUTFALL
30m W
OUTFALL LINE
30m E
84m E
SURFACE
5 feet (1.5 meters)
10 feet (3.0 meters)
20 feet (6.1 meters)
40 feet (12.2 meters)
<36

Figure 13. Aerial perspectives of contours of percent light transmission at Combined Sewer Outfall 023--1330-2330 hrs., 2/6/79

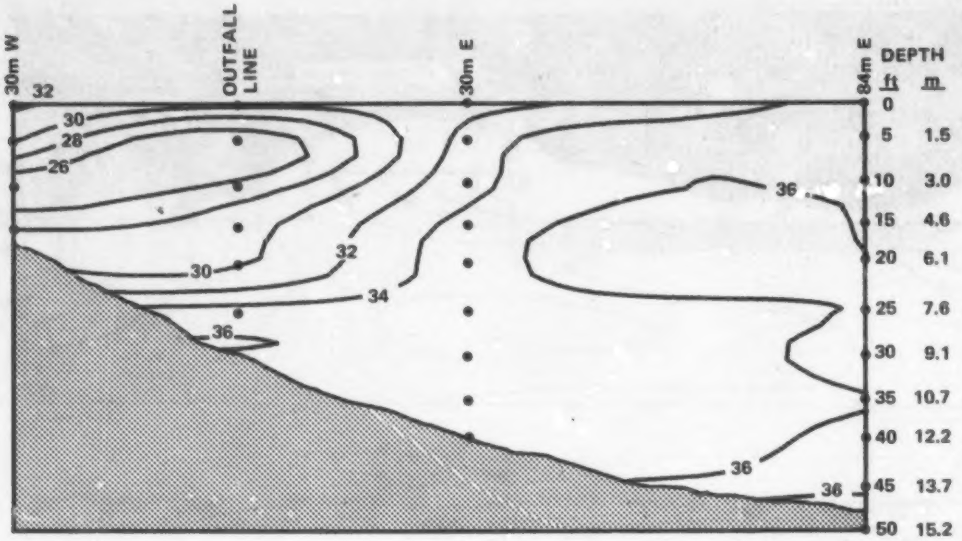


Figure 14. Transverse section through a point 34 m S of Combined Sewer Outfall 023 showing contours of percent light transmission--1330-2330 hrs., 2/6/79. The perspective is that of a diver with the shore to his left.

Offshore settling of discharge solids was also observed during these storms. Figure 17 gives a time sequence of light transmission distributions for the onshore-offshore transect 61 m north ("downstream") of the SD 7 outfall. The first distribution was recorded immediately following cessation of the 2/6/79 storm discharge; the second was recorded three hours later. The dissipation and settling of particulates offshore is evident. An even more graphic portrayal of this effect is given by Figure 18, which represents the light transmission distribution along a transect 283 m farther north, and immediately offshore of the second storm drain, at the time of the distribution in Figure 17b. Such patterns, with turbid plumes moving offshore along or near the bottom were observed frequently during the several storms monitored at SD 7.

Control Site 3 -- The C 3 area was found to be inundated with suspended particulate matter from a variety of sources. Light transmission contours drawn for storm data collected on 2/12/79 show the local response to an estimated 3.15 cm (1.24 in) of rain (Figures 19 and 20).

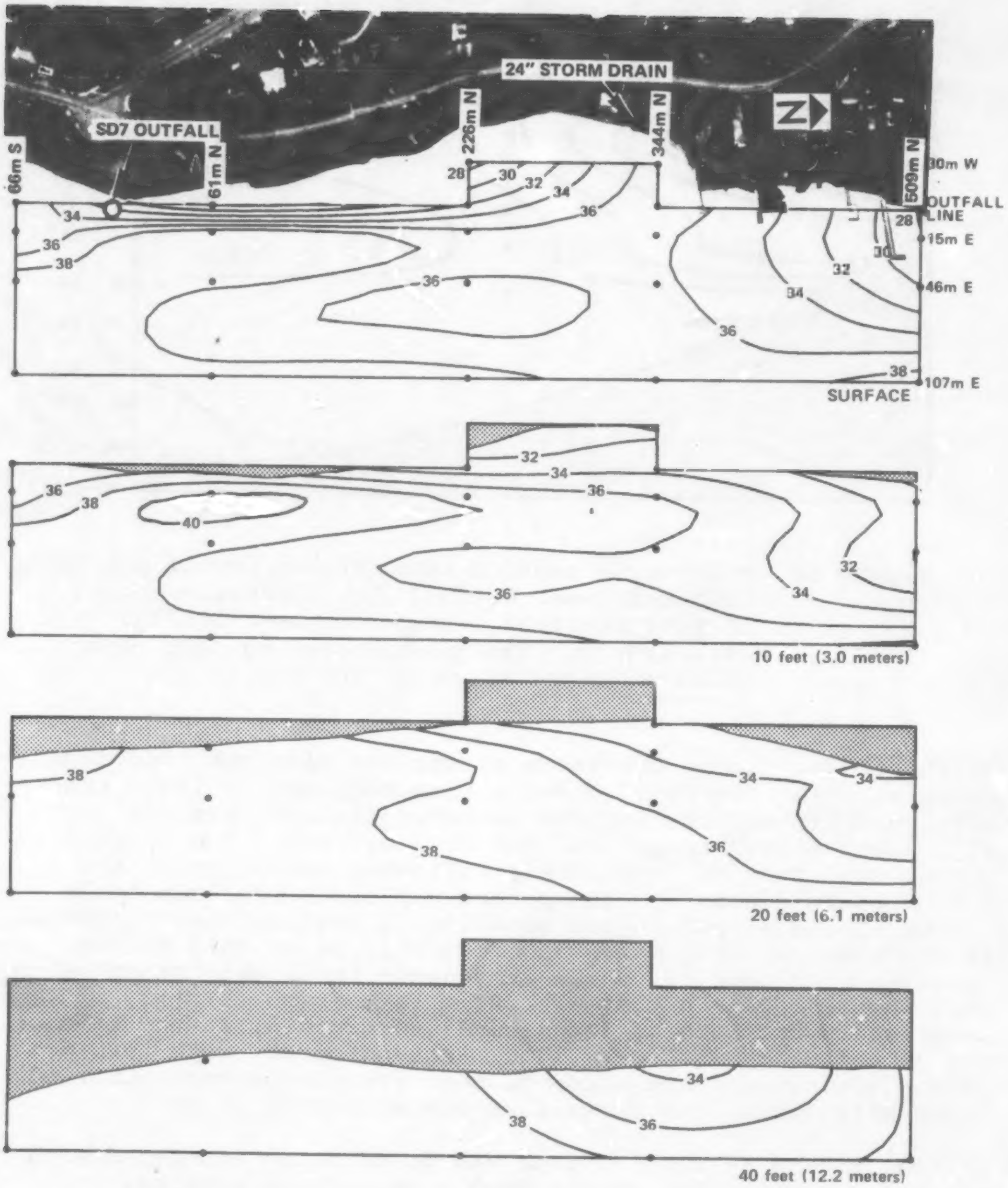

24" STORM DRAIN
SD7 OUTFALL
66m S
61m N
226m N
344m N
509m N
30m W
OUTFALL LINE
15m E
46m E
107m E
SURFACE
10 feet (3.0 meters)
20 feet (6.1 meters)
40 feet (12.2 meters)
28
30
32
34
36
38
40

Figure 15. Aerial perspectives of contours of percent light transmission at Storm Drain 7--1915-2014 hrs., 2/6/78.

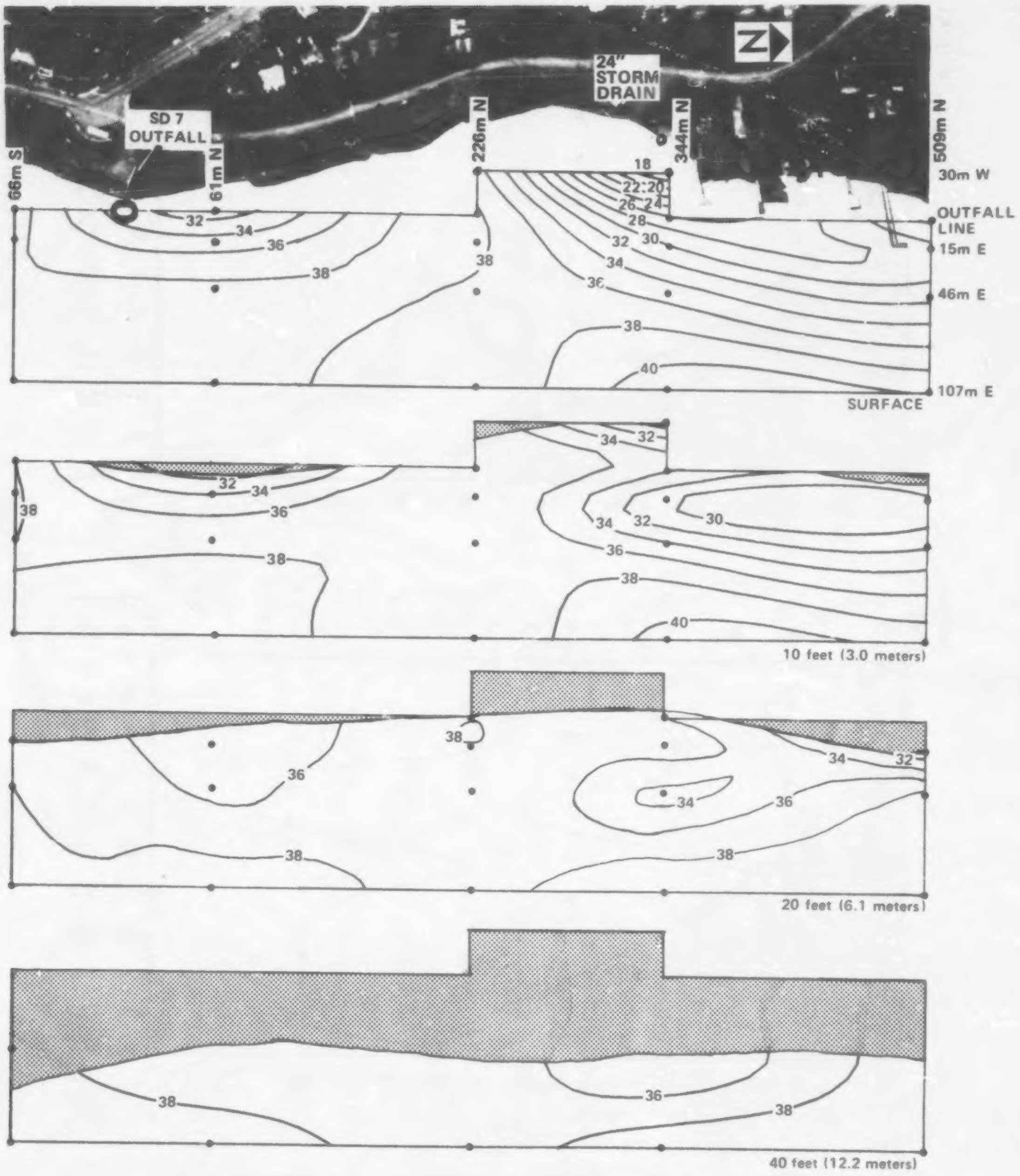
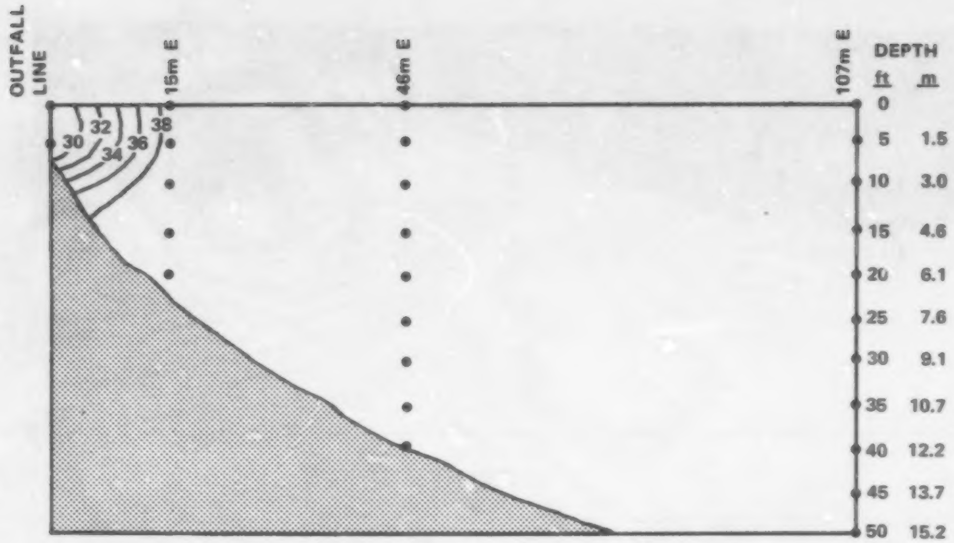
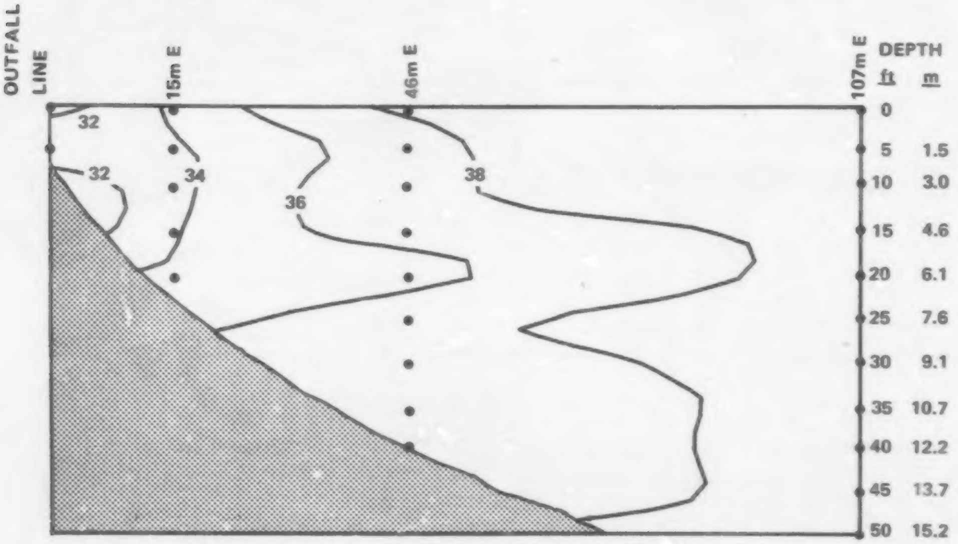


Figure 16. Aerial perspectives of contours of percent light transmission at Storm Drain 7--2244-2348 hrs., 2/6/79.



(a) One hour after cessation of storm discharge by SD 7 (1915-2014 hrs).



(b) Four hours after cessation of storm discharge by SD 7 (2244-2348 hrs).

Figure 17. Transverse sections through a point 61 m N of Storm Drain 7, showing contours of percent light transmission on 2/6/79. The perspective is that of a diver with the shore to his left.

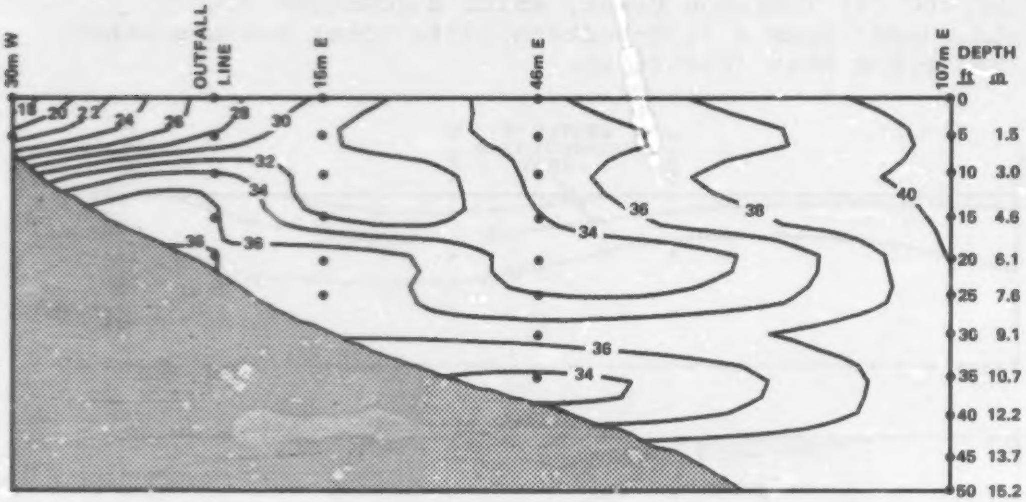


Figure 18. Transverse section through a point 344 m N of Combined Sewer Outfall 023, showing contours of percent light transmission—2244-2348 hrs., 2/6/79. The perspective is that of a diver with the shore to his left.

An uncharted source of storm drainage was indicated at the surface, inshore and 70 m N of the center of the sediment trap array. Considering the large volume of rain incident on the adjacent hillside, and the mild response indicated, the drainage system implicated must have been small. The sampling was done approximately midway through the 36-hour storm period.

A second major input of particulates is evident below the 9 m depth in Figure 20, and in the 15 m section in Figure 19 The presence of an extensive turbid layer moving at depth through a comparatively natural area of the lake was unexpected, and would seem to constitute a large-scale phenomenon. Although the circulation in this area was found to be complex, with multiple surface drift observations indicating intermittant flow to the southwest and northeast, the prevailing flow would necessarily be southwesterly, carrying basin runoff toward the Lake Washington outlet to Puget Sound (Figure 2). Accordingly, the deep, turbid layer observed at C 3 on 2/12/79 is believed to have been a longshore flow of settling particulates moving from the northeast. The most likely sources of this material were (1) a series of 22 storm drains (including eight ≥ 60 cm diameter) carrying runoff from an area of active construction 0.7-3.8 km to the north, and (2) Thornton Creek, which discharges highly turbid runoff from a 3130-hectare (7740-acre) basin another 0.4 km beyond that (Figure 2).

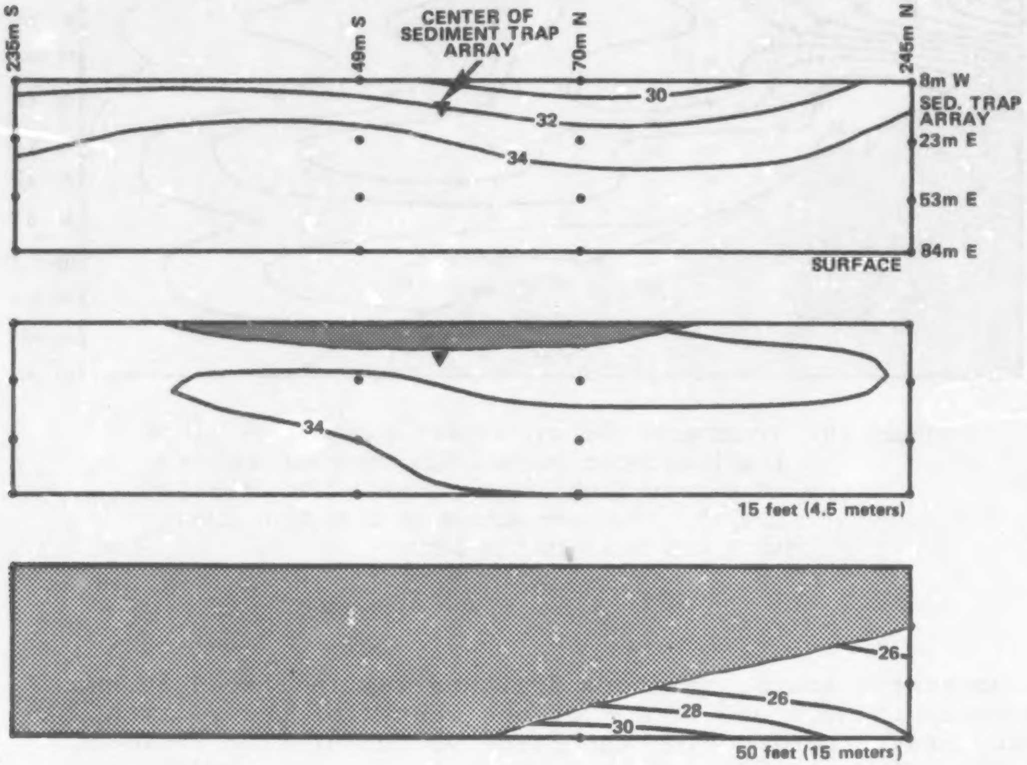
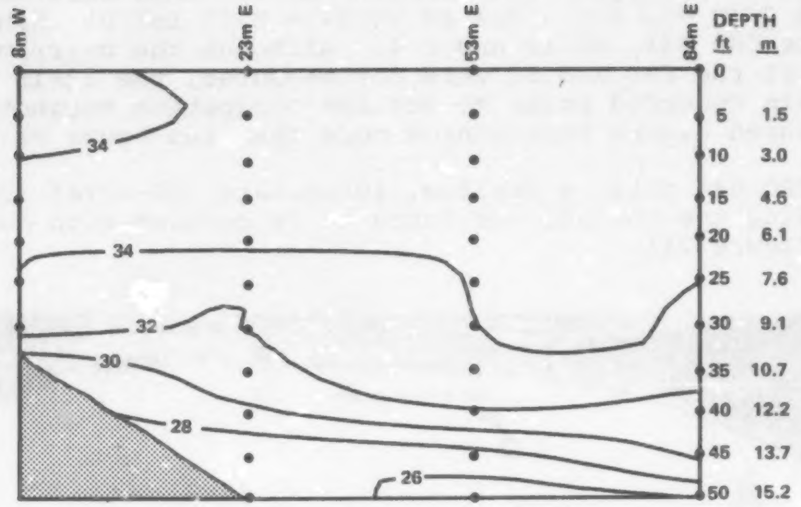


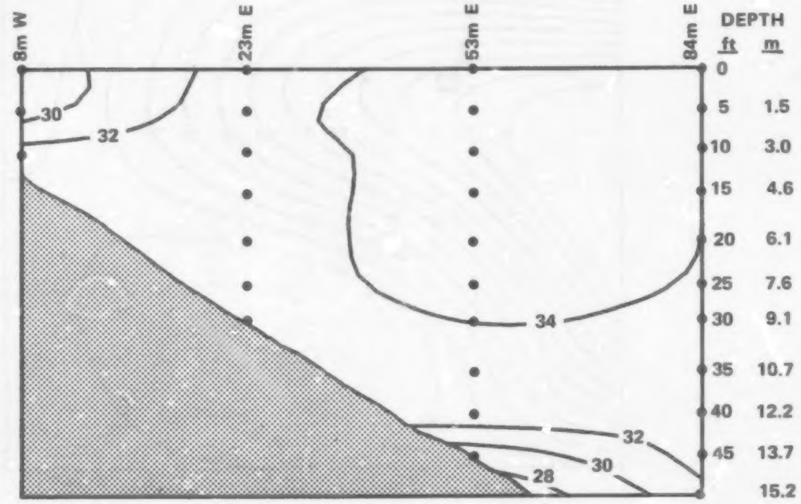
Figure 19. Aerial perspectives of contours of percent light transmission at Control Site 3--0506-0549 hrs., 2/12/79.

The nature of turbid longshore advection through the C 3 area seemed to be quite variable--an extensive particulate layer observed entering from the north on 3/25/78 was on the lake surface, whereas that mentioned above was at depth. Regardless, the sediment quality analyses done in the course of this project indicated only light settling of contaminated particles in this area, and the measured settling rate was substantially lower than for the CSO 023 and SD 7 areas. These concepts are discussed in more detail below.

CSO 044, SD 19 and Control Site 4 -- A second set of three nearshore areas was monitored during a single storm to provide support data for the biological studies and for the



(a) 245m N of sediment trap array.



(b) 70m N of sediment trap array.

Figure 20. Transverse sections showing contours of percent light transmission at Control Site 3--0506-0549 hrs., 2/12/79. The perspective is that of a diver with the shore to his left.

discharge dispersion trends observed at CSO 023, SD 7 and C 3. By the time the light transmission measurements were made on 2/11 and 2/12/79, 2.1 - 2.4 cm (0.84 - 0.93 in) of rain had fallen at CSO 044, SD 19 and C 4. Although the overflow volumes at the CSO and SD were not measured, the 12-16 hr of heavy rain recorded prior to station occupation suggest that the measured plumes represented more than ten hours of discharge.

At the CSO 044 site, a shallow, 10-hectare (25-acre) area surrounding the outfall was found to be covered with discharge plume (Figure 21).

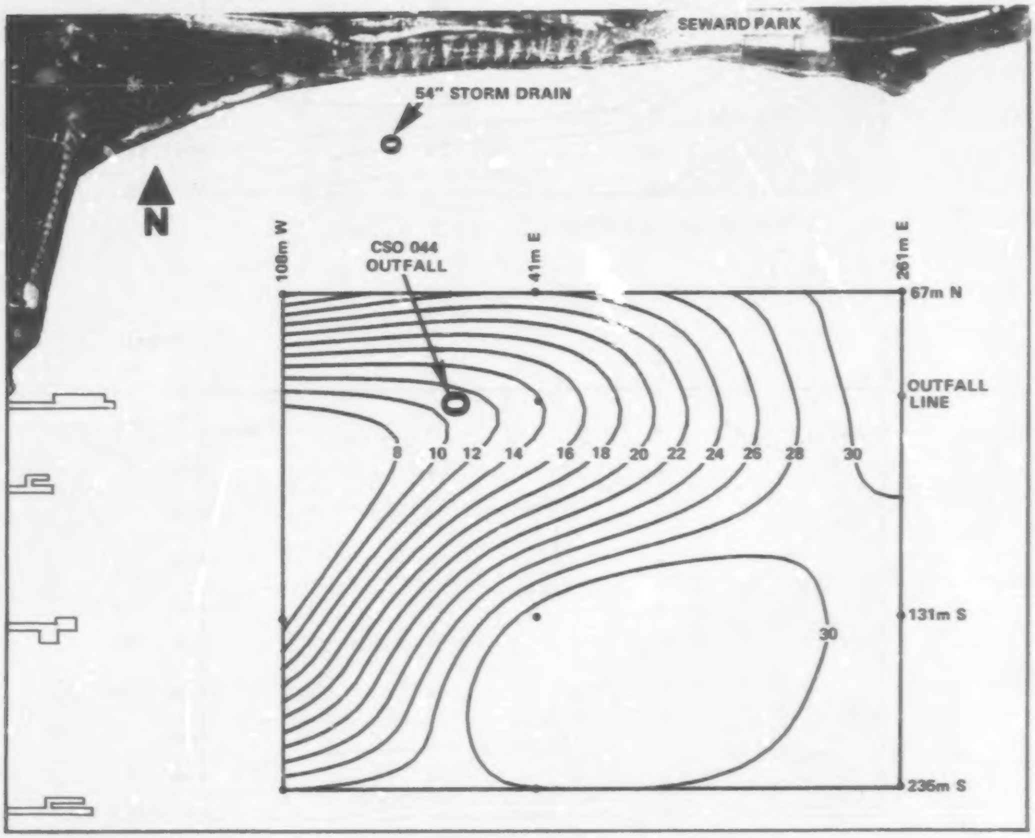

SEWARD PARK
54" STORM DRAIN
N
108m W
CSO 044
OUTFALL
41m E
261m E
67m N
OUTFALL
LINE
8
10
12
14
16
18
20
22
24
26
28
30
131m S
30
236m S

Figure 21. Aerial perspectives of contours of percent light transmission at Combined Sewer Outfall 044--2210-2350 hrs., 2/11/79.

The isopleths of light transmission for this area were predominantly vertical from the surface to the bottom at 6 m; there was some indication of near-bottom movement toward the northeast, i.e., countercurrent to the apparent surface drift. The magnitude of discharge contribution from the 137 cm storm drain northwest of the CSO 044 outfall is unknown, but was probably considerable.

The turbidity patterns monitored around the SD 19 outfall during the same storm showed an added dimension of complexity due to an extremely dense load of particulates moving past from the south. These solids undoubtedly were part of the storm load from the Cedar River (Figure 2). The turbid surface layer related to this phenomenon was homogeneous to a depth of 9 m and had light transmission readings as low as 10% (Figure 22).

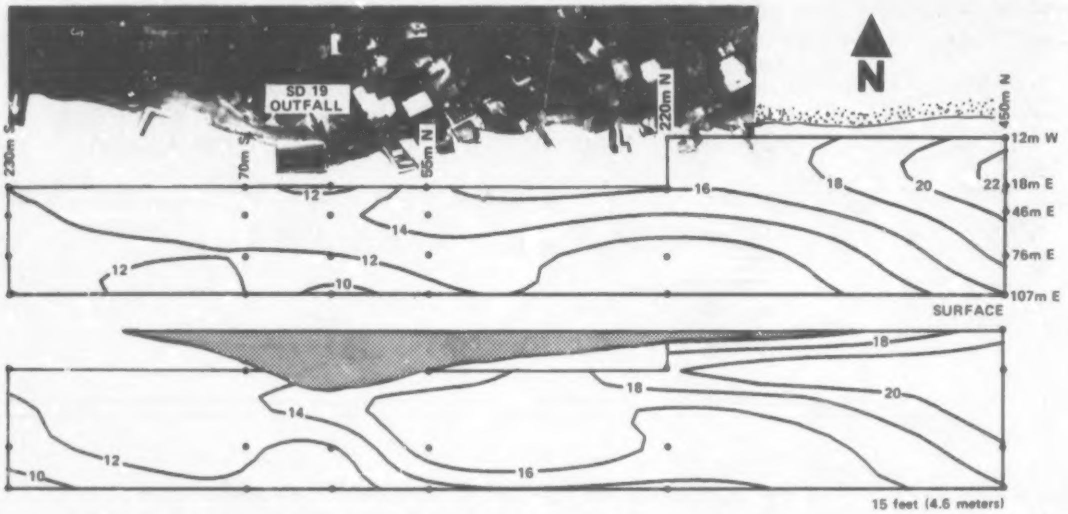


Figure 22. Aerial perspectives of contours of percent light transmission at Storm Drain 19--0020-0250 hrs., 2/12/79.

The SD 19 outfall was simultaneously injecting turbid discharge into the nearshore waters. The longshore movement of this plume to the northeast trapped a wedge of comparatively clear ambient water between it and the river discharge farther offshore. Dense clouds of discharge particulates were also detected sliding offshore along the transect lines 10 m S, 55 m N and 220 m N of the outfall; the net effect of this movement under the river layer was to isolate a second parcel of ambient water with core depths ranging between 5 m and 12 m and approximately 60 m offshore. Storm drainage from SD 19 was not found on the transects 70 m and 230 m south of the outfall.

The light transmission measurements made at Control Site 4 during the storm of 2/12/79 revealed no coherent structure. Values at all depths ranged between 40.5% and 43.5% light transmission.

Quantification of Particulate Contaminants -- Sedimentation Rates and Chemical Constituents -- A total of 18 sediment traps were moored in arrays of six at CSO 023, SD 7 and C 3 (Figure 7). The settling particulates captured by these devices were collected periodically between January, 1978 and February, 1979. and analyzed for total dry weight, total C, total P, Pb, Zn, Cu and Al.

The degree to which the measured sedimentation rates reflected the volume of discharge at CSO 023 and SD 7 for each sampling period was estimated by linear regression. The correlation coefficients (r) are given in Table 10.

TABLE 10. CORRELATION COEFFICIENTS FOR NEARSHORE SEDIMENTATION RATES VS. VOLUME OF DISCHARGE FROM COMBINED SEWER OUTFALL 023 AND STORM DRAIN 7

Station	Discharge Type	Corr. Coeff.
CSO 023	Storm	.852
SD 7	Storm	.290
	Storm + Nonstorm	.157

Storm Drain 7 flows continuously, and therefore sedimentation rates were regressed against both storm discharge and total (storm + nonstorm) discharge in order to define the relative strength of these relationships. Neither value of r determined for this station indicated a close relationship between discharge volume and sedimentation rate. These findings are in accordance with previous observations that much of the discharge plume characteristically bypassed the SD 7 sediment trap array. The opposite was found for CSO 023, where the comparatively high correlation coefficient of 0.852 implied a close relationship; the plume at this station was typically over the sediment traps.

Table 11 is a summary of the results of a series of two-way analyses of variance performed for the various sediment trap parameters, using stations and collection periods as variables. These results indicate that there was significant interaction between stations and collection periods on sedimentation rate. This finding is reasonable since collection periods

TABLE 11. SUMMARY OF RESULTS OF TWO-WAY ANALYSIS OF VARIANCE FOR SEDIMENT TRAP COLLECTIONS FROM COMBINED SEWER OUTFALL 023, STORM DRAIN 7, AND CONTROL SITE 3, USING STATION AND SAMPLING PERIOD AS VARIABLES

		Significance[b]		
Element[a]	Number of Sample Sets	Between Stations	Between Periods	Interaction
Sed. Rate (g/m^2/day)	11	0.01	0.01	0.01
Total C (%)	9		0.01	0.05
Total P (%)	11		0.01	
Pb (mg/kg)	11	0.01	0.01	0.01
Zn (mg/kg)	11		0.05	0.05
Cu (mg/kg)	11	0.05	0.01	
Al (%)	11	0.01	0.01	0.05

(a) All data based on dry weight of particulates.
(b) Level of α .

TABLE 12. MEAN SEDIMENTATION RATES AND DRY WEIGHT CONCENTRATIONS OF SELECTED CONSTITUENTS ANALYZED IN SEDIMENT TRAP SOLIDS COLLECTED AT COMBINED SEWER OUTFALL 023, STORM DRAIN 7 AND CONTROL SITE 3, 1/30/78-2/2/79

	CSO 023		SD 7		C 3	
	$\overline{X}$	S_x[a]	$\overline{X}$	S_x	$\overline{X}$	S_x
Sed. Rate (g/m^2/day)	.752	.714	.805	.696	.268	.199
Total C (%)	9.58	3.85	9.29	4.53	9.34	6.08
Total P (%)	.252	.192	.212	.211	.273	.205
Pb (mg/kg)	366	104	521	355	245	97.1
Cu (mg/kg)	126	108	94.8	44.8	70.8	41.8
Zn (mg/kg)	349	152	286	127	244	125
Al (%)	4.26	1.07	4.70	1.13	3.72	1.09

(a) One standard deviation.

reflect seasonal variability of discharge, with CSO 023 and SD 7 having their greatest increases in sedimentation rate (compared to that measured for C 3) during periods of storm runoff. Even though collection period and station are thus shown not to be independent variables, it is clear that both CSO 023 and SD 7 had significantly higher sedimentation rates than did the control site.

The mean sedimentation rates in $g/m^2/day$ (Table 12) from 1/30/78 to 2/2/79 were .752 for CSO 023, .805 for SD 7 and .268 for C 3. A relative value for the adjacent profundal area is .661, which was determined by correcting a rate measured at 60 m depth (Birch, 1976), for the offshore movement of particulates entering the lake in the littoral zone. This correction was based on the observation that the area of permanent sediment accumulation in Lake Washington is about 50% of the total surface area, and measured profundal values must therefore be halved to render them comparable to littoral measurements. The offshore sedimentation rate is, then, less than nearshore values measured in the vicinity of the outfalls, but greater than that determined for the control area. A significant fraction of the suspended particulates in the study areas is transient material which eventually contributes to the sedimentation rate in the profundal zone.

The flux, or quantity settling through a given cross-sectional area per unit time, of particulate C, P, Pb, Cu or Zn was computed as the product of the constituent concentration (weight/total weight of solids) and the sedimentation rate. Compared to CSO 023 and SD 7, the control site had similar or lower concentrations of each of the measured constituents (Table 12) and a significantly lower sedimentation rate. The flux of all solid elements at C 3 was therefore significantly lower than at CSO 023 or SD 7.

The analysis of variance for total carbon, Table 11, shows that the most significant variability can be attributed to collection periods, and that there were no significant differences between stations. The major source of measured carbon, for which the highest concentrations occurred during the summer months, appeared to be periphytic algae growing on the sediment traps. Comparatively high negative correlations ($r=-.461$, $-.423$ and $-.538$ for CSO 023, SD 7 and C 3, with $\alpha = .01$ for each) were calculated for %C vs. sedimentation rate. This relationship can be attributed to the effects of dilution by inorganic material during periods of high sedimentation, and concomitant low light intensity (meaning decreased periphytic photosynthesis). These phenomena are typical of rainstorm and high-discharge conditions.

The trend for phosphorus was similar to that seen for carbon, with significant differences in concentration between collection periods, but not between stations. Whereas there were moderate correlations determined between C and P for CSO 023 (r=.264) and SD 7 (r=.291), the correlation for the control site (r=.660) was appreciably stronger. This points to photosynthetic production as the common major source of C and P in particulates settling in the control area.

The average concentrations of Pb in the sediment trap solids were 366 mg/kg at CSO 023, 521 mg/kg at SD 7 and 245 mg/kg at C 3, with the differences between stations found to be significant at the 99% confidence level. These values are in keeping with the relative Pb discharge evaluations discussed previously, which showed SD 7 to be much higher than CSO 023 in this respect (Tables 5 and 6).

Cu and Zn had similar concentration hierarchies: CSO 023 > SD 7 > C 3. According to the statistical results listed in Table 11 the between-station differences were not significant for Zn, although some station-period interaction was indicated; the opposite was true for Cu, possibly indicating notably different sedimentation mechanisms for these two metals in the nearshore environment.

Aluminum was analyzed as a conservative tracer of erosional inputs to the system because it is a major sediment constituent (3-10% of solids dry weight), and there are no non-erosional sources of Al in the Lake Washington drainage basin. Correlation coefficients calculated for sediment trap concentrations of Al vs. storm discharge rates were .909 for CSO 023 and .363 for SD 7, the latter value being lower due to the tendency of the SD 7 plumes to bypass the sediment traps, as determined by light transmission measurements - the plumes were typically found near shore in water too shallow for sediment trap moorings. The mean Al concentrations determined for settling particulates collected near both outfalls were significantly higher than for solids from the control site, indicating a greater input of erosional matter at the outfall sites.

Viruses -- Table 13 is a compilation of data representing virus analyses performed on receiving water samples collected at CSO 023 and SD 7 during and after storm discharges. As was expected from the previously-discussed lack of viruses in the SD 7 discharge, none were found in the receiving waters either. During an overflow at CSO 023, however, viruses were detected at a level representing an estimated end-of-pipe dilution of 32:1, the ratio of discharge concentration (10/23/78 sample, Table 7) to concentration in the receiving waters (2/6/79 sample, Table 13). These two samples were both collected during times of (assumed) light use of sanitary facilities; for this reason it is suspected that higher concentrations might be observed in the receiving waters during peak-hour overflows (refer to discussion of discharge

TABLE 13. SUMMARY OF VIRUS ANALYSES OF RECEIVING WATERS NEAR COMBINED SEWER OUTFALL 023 AND STORM DRAIN 7 DURING AND AFTER STORM DISCHARGE

Station/Condition	Date	Discharge Volume (m^3)	Number of Viruses/m^3	Recovery Efficiency (%)
CSO 023/Discharging	2/6/79	155	6600	3.7
24 hr Post-Discharge	2/ '79	155	0	3.1
SD 7/Discharging	2/10/79	335	0	3.2
24 hr Post-Discharge	3/6/79	1880	0	2.4

virus analyses). The receiving water samples were collected near the outfalls in patches of minimum light transmission in order to optimize the chances of sampling the discharge plume. As mentioned previously, however, plume separation does occur due to particle size and density differences, so that the measured virus concentrations may not represent maxima.

The 24 hr post-overflow sample was in each instance taken from the same location as those collected during the overflow. No viruses were detected at CSO 023, indicating that the plume had dispersed, an observation confirmed by transmissometer readings.

Sediment Measurements --

Particle Size Distributions -- Fifteen particulate samples were analyzed for percent organic content and grain-size distribution. These samples included sediments from N, NE, SE and S of the CSO 023 outfall and NE and SE of the SD 7 outfall. Also, end-of-pipe sediments and discharge particulates were analyzed for both stations. Because large station-to-station sediment variations were observed by divers even in areas relatively free of outfalls, no single location was designated for control measurements; rather, trends were sought within each area that might relate to an outfall location and the characteristics of the discharge particulates.

The resultant data were summarized in terms of four parameters for each sample: organic content, median particle diameter, sorting coefficient and skewness. The latter three variables collectively represent the shape of a particle size distribution curve (Sverdrup et al., 1942, p. 970). Figure 23 is a summary of this information.

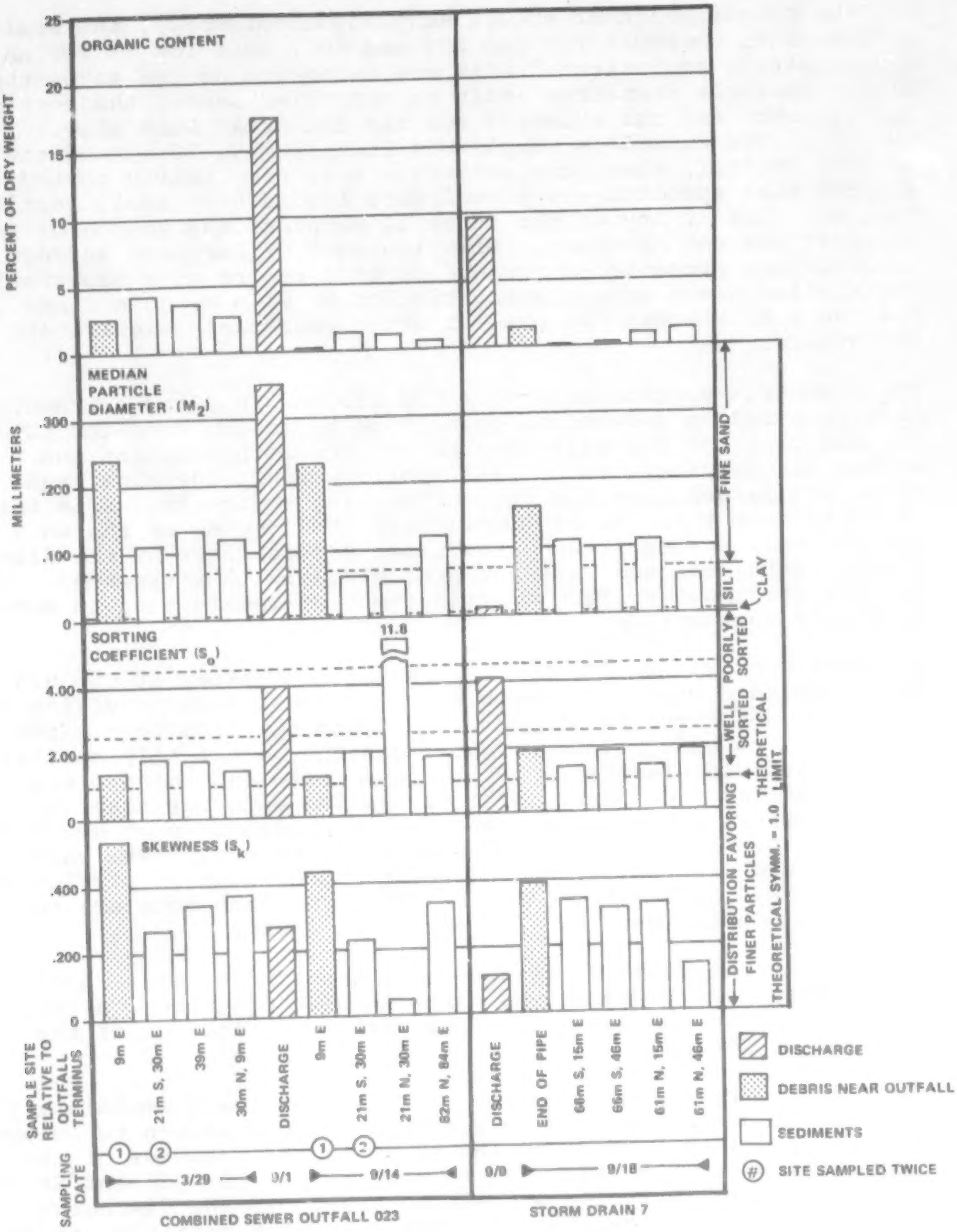


Figure 23. Summary of results of particle size distribution analyses for Combined Sewer Outfall 023 and Storm Drain 7.

For the single month of mutual sampling (September), the sediment organic contents for CSO 023 and SD 7 were low (< 2%) and approximately equivalent. With the exception of one site, the median particle diameters (silt to very find sand), the sorting coefficients and the skewness for the two areas were also similar. The anomalous sample was from 21 m N, 30 m E of the CSO 023 outfall, where the sediments were very poorly sorted and the size spectrum was skewed more toward very small particles than was that of any of the other 14 samples; the source of this material was not apparent. Distributions of sediment surface contaminants presented elsewhere in this report give expectations for similar grain size characteristics at 21 m N, 30 m E and 21 m S, 30 m E, whereas the present data demonstrate significant differences.

The discharge particulates from CSO 023 and SD 7 had extremely disparate median diameters, being fine to medium sand for the CSO and clay to fine silt for the SD; for both stations the median diameters of the outfall debris were in the fine sand range and larger than for the surrounding sediments. From this, it would seem that the sediments near the opening of the SD 7 outfall were washed free of the finer particulates by the discharge turbulence and were not predominantly of wastewater origin. Sediment surface distributions of metals tend to confirm this supposition.

As denoted by Figure 23, two of the sediment sites at CSO 023 were sampled during both March and September, thus providing a seasonal comparison of parameters. Sediments from both sites were found to have a lower organic content, a slightly smaller median particle diameter, comparable sorting and to have distributions favoring finer particulates in September than in March. Generally speaking, these are the changes that one might expect to occur during a dry period with few overflows, when organics are dissipated and the natural breakdown of particulates is not masked by fresh wastewater inputs. These data are too few to be conclusive, but the trends are logical.

Considering the relative site-to-site magnitudes for each of the three parameters representing particle-size distribution (M_2, S_o and S_k), one can generalize the pertinent findings of the analyses as follows:

The particle-size distributions of sediments lying immediately in front of discharges may be altered by the emission turbulence. The most prominent effect is the shift in the skewness of the distributions toward larger particles (as for CSO 023 and SD 7), i.e., the finer particles are washed away. If the discharge particulates themselves have a relatively high median particle diameter (as for CSO 023), a significant portion may settle close to the outfall, altering the median size accordingly. Simultaneously, the settling of the larger particles and washing away of the smaller ones could be expected to improve the sorting. If the discharge particulates are comparatively small (as for SD 7), they will likely be carried further from the outfall before settling.

Core Analyses -- To help define trends of movement and accumulation of discharge particulates in the receiving waters, sediment cores were collected at the transmissometer grid sites at CSO 023, SD 7 and C 3. A total of 56 cores were dried, sectioned and analyzed for Pb, Zn, Cu, P and total carbon. Contoured distributions of some of these constituents in the 1-cm sediment surface layer are presented here in Figures 24, 25, and 26. In view of the typically patchy nature of aquatic sediment distributions, particularly in areas subjected to current action and a variety of anthropogenic influences, this information should be used as a means to visualize general trends, and not for detailed comparisons. The contours show enrichment of the sediments near the two outfalls, with apparent distribution modification from current action and near-bottom downslope streaming. Table 14 lists the significant ($\alpha = .05$) differences between the stations for each of the measured constituents; these were determined by a one-way analysis of variance followed by the application of Scheffe's procedure for linear contrasts (Scheffe, 1959).

TABLE 14. SIGNIFICANT DIFFERENCES ($\alpha = .05$) BETWEEN MEAN STATION CONCENTRATIONS FOR SELECTED PARAMETERS ANALYZED IN THE TOP 0.5 CENTIMETER OF SEDIMENT CORES COLLECTED AT COMBINED SEWER OUTFALL 023, STORM DRAIN 7 AND CONTROL SITE 3

Wet wt./dry wt.	CSO 023 > SD 7
Total C	CSO 023 > SD 7 CSO 023 > C3
Total P	None
Pb	CSO 023 > C3
Zn	CSO 023 > SD 7 < C3
Cu	CSO 023 > C3 SD 7 > C3

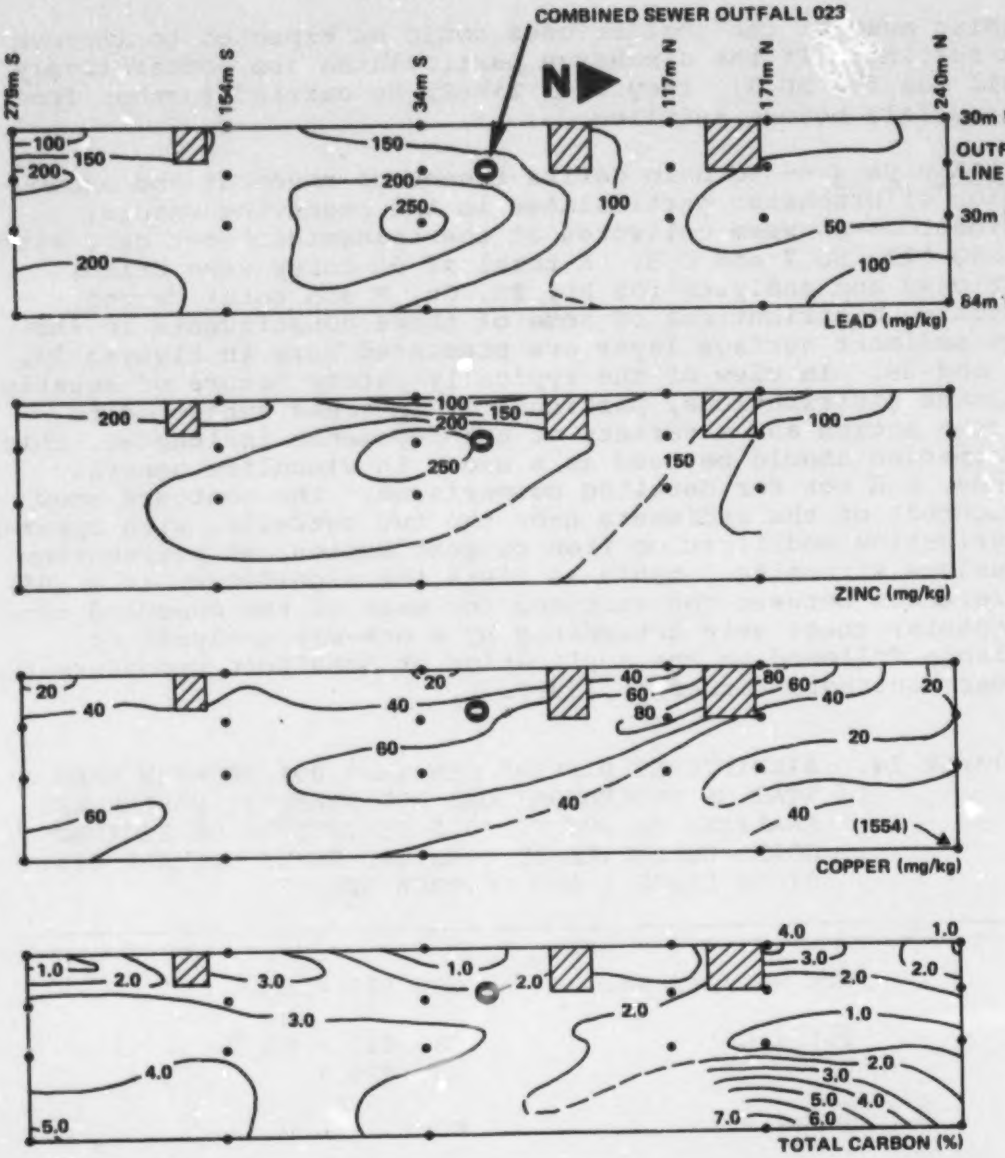

COMBINED SEWER OUTFALL 023
N
278m S
154m S
34m S
117m N
171m N
240m N
30m W
OUTFALL LINE
30m E
84m E
LEAD (mg/kg)
100
150
200
250
50
ZINC (mg/kg)
COPPER (mg/kg)
20
40
60
80
(1554)
TOTAL CARBON (%)
1.0
2.0
3.0
4.0
5.0
6.0
7.0

Figure 24. Dry weight distributions of lead, zinc, copper and total carbon in the surface centimeter of sediments collected near Combined Sewer Outfall 023.

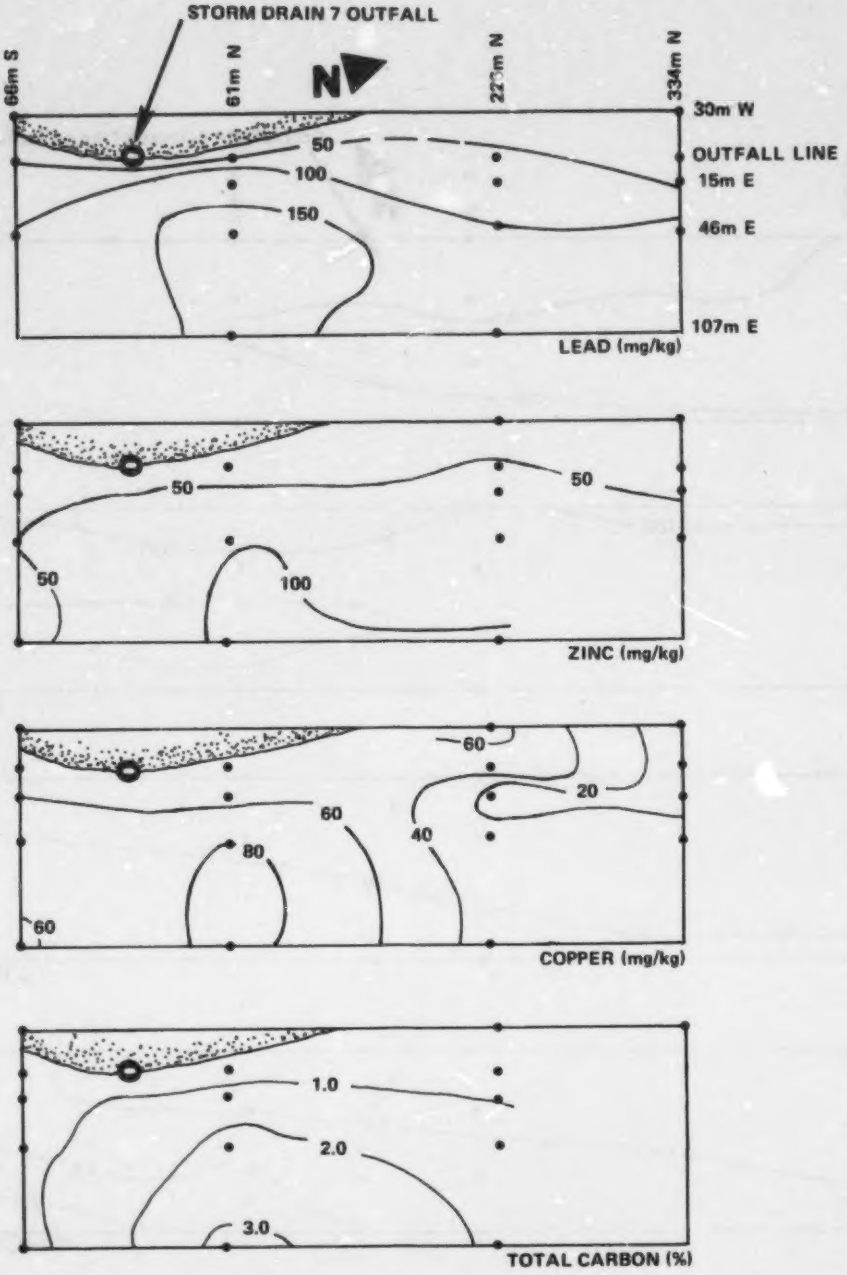

STORM DRAIN 7 OUTFALL
66m S
61m N
N
223m N
334m N
30m W
OUTFALL LINE
15m E
46m E
107m E
50
100
150
LEAD (mg/kg)
50
50
50
100
ZINC (mg/kg)
60
20
60
40
80
60
COPPER (mg/kg)
1.0
2.0
3.0
TOTAL CARBON (%)

Figure 25. Dry weight distributions of lead, zinc, copper and carbon in the surface centimeter of sediments collected near Storm Drain 7.

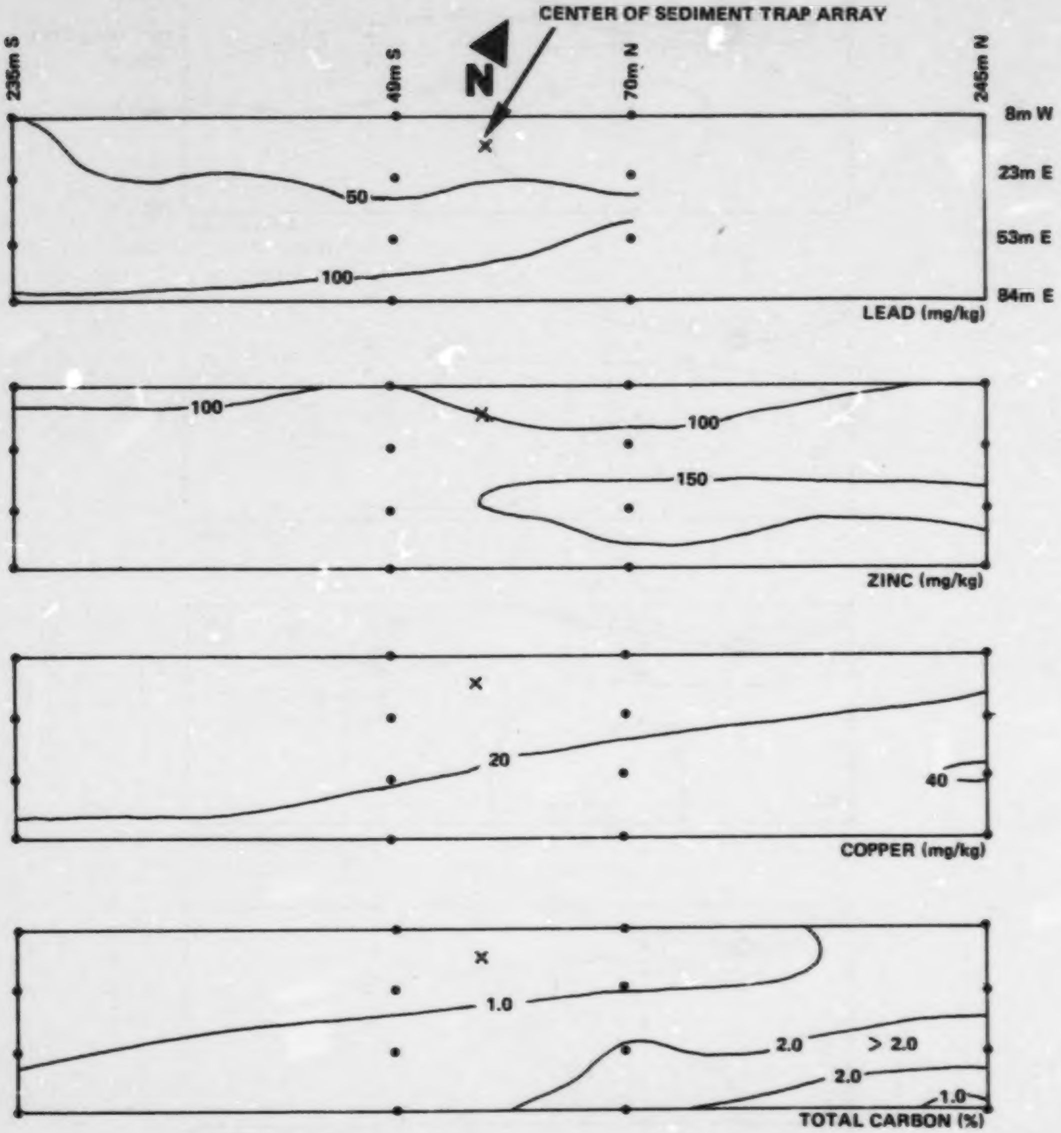


Figure 26. Dry weight distributions of lead, zinc, copper and total carbon in the surface centimeter of sediments collected at Control Site 3.

These comparisons indicate tendencies for CSO 023 to have the highest mean concentrations of discharge contaminants found in the thin, transitory sediment surface layer. Overall, SD 7 was not found to be significantly different than C 3 in this sense, this was predominantly due to the comparatively rapid movement of discharge particulates out of the sampling area, as is apparent from the distributions in Figure 25. Further, evidence is given below to show that the C 3 control site itself has been contaminated by particulates advected from remote sources.

Table 15 is a compilation of metals data for particulates sampled at the three principal study sites. These numbers provide a useful aid for tracing the movements of discharge solids. The concentrations of metals in the sediment trap

TABLE 15. MEAN CONCENTRATIONS[(a)] AND CONCENTRATION RATIOS FOR SELECTED METALS IN PARTICULATES SAMPLED AT COMBINED SEWER OUTFALL 023, STORM DRAIN 7 AND CONTROL SITE 3

		Mean Concentration (mg/kg)					
Location	Source	Pb	Zn	Cu	Pb:Cu	Zn:Cu	Zn:Pb
CSO 023	Discharge[(b)]	257	560	265	1.0	2.1	2.2
	Sed. Traps	366	349	126	2.9	2.8	0.9
	0-0.5 cm Sed.	129	168	39	3.3	4.3	1.3
	7-8 cm Sed.	51	92	40	1.3	2.3	1.8
SD 7	Discharge[(b)]	2377	785	333	7.1	2.4	0.3
	Sed. Traps	521	286	95	5.5	3.0	0.5
	0-0.5 cm Sed.	89	61	47	1.9	1.3	0.7
	7-8 cm Sed.	46	35	42	1.1	0.8	1.4
C 3	Sed. Traps	245	244	71	3.5	3.4	1.0
	0-0.5 cm Sed.	86	131	20	4.4	6.6	1.5
	7-8 cm Sed.	21	51	7	2.9	7.1	2.5
Profundal[(c)]	0-1 cm Sed.	192	192	46	4.2	4.2	1.0
	Pre-1900 Sed.	12	59	17	1.0	3.5	3.5

(a) Dry Weight.
(b) Calculated from data in Tables 5 and 6, as mg/kg of suspended solids in the discharge.
(c) From ^{210}Pb-dated cores collected in the deep central basin of Lake Washington, between CSO 023 and SD 7 (Spyridakis and Barnes, 1976).

collections were generally 2-5x those of the 0-0.5 cm sediment surface layer. This observation implies selective removal to deeper areas, of the finer particulates, with which the highest metal concentrations are typically associated (Guy and Chakrabarti, 1976). Sediment cores collected along across-lake transects contiguous to CSO 023 and SD 7 and to a major secondary treatment plant outfall abandoned in 1968 clearly show an increase of Pb, Zn and Cu concentrations with lake depth (Barnes, 1979). As is evident from a comparison of the CSO 023 and SD 7 sediment trap data with values for profundal (deep offshore) surface sediments, however, the latter materials have been appreciably diluted by relatively uncontaminated secondary sources, including diatoms and river detritus. Barnes and Spyridakis (1976) have estimated that contemporary fluvial inputs (including CSO and SD discharges) are responsible for 26%, 90% and 53%, respectively, of the Pb, Cu and Zn entering the lake.

This offshore movement of discharge particulates is also evident in the distributions of sediment metals near the two outfalls. The isopleths for Pb and Zn around CSO 023 (Figure 24) show the effects of near-bottom turbidity plumes moving downslope to the southeast (refer to Figure 3 for areal bathymetry). For Cu, the concentration isopleths imply the additional influence of advective transport toward the northwest, where the particulates settled due to flow disruption by condominium support pilings. Although the prevalent direction of flow of subsurface currents at the CSO 023 site was not clearly defined by the light transmission studies, the northwesterly advection implied by the sediment distributions is logical as the most direct route to the flow outlet for Lake Washington (Figure 2). The considerable differences in sediment distributions for Pb and Zn vs. Cu indicate that the Cu-bearing particulates were smaller and/or lighter, and thus more easily influenced by water motion. Carbon was found to be more widely dispersed than the metals, in keeping with the nature of the large, light carbon-bearing particulates. Correlation coefficients calculated for Cu, Pb and Zn vs. C in the surface layer of the bottom sediments were .646, .415 and .238, respectively, implying that the relatively light Cu and C particulates have the most similar transport characteristics, and further confirming the Cu > Pb > Zn dispersion hierarchy suggested by Figure 24.

The selective transport tendencies of Cu, Pb and Zn at CSO 023 are also delineated by the concentration ratios given in Table 15. The Zn:Cu ratio increases as the particulates move from the outfall to the traps, and again, from the traps to the sediments; this is because of the higher losses of Cu through advective transport. The decrease of the Zn:Pb ratio represents an external input to this system -

particulate Pb contributions from aeolian transport (Spyridakis and Barnes, 1976). The subsequent increase in the Zn:Pb ratio between the traps and the sediments implies a shorter local residence time for Pb. All of the sediments above 8 cm depth at CSO 023 have been deposited since the addition of tetraethyl lead to gasoline in the late 1920s, as is evident from their substantial Pb enrichment relative to pre-1900 (background) concentrations.

As noted in previous discussions relative to SD 7, substantial advective losses of wastewater particulates from the sampling area result in a considerably different pattern of local deposition compared to that seen at CSO 023. Near the SD 7 outfall, the sediment distributions of Pb, Zn, Cu and C were all found to be quite similar (Figure 25), showing the dominant influence of near-bottom downslope streaming just north of the outfall.

Comparisons of median discharge particle diameter (refer to discussion of grain size distributions, above) showed that the wastewater particulates emitted by SD 7 were much smaller than those from CSO 023, facilitating advective losses. This observation helps to account for the comparatively precipitous drop of particulate metals concentrations between the SD 7 discharge and the sediment traps; the concentrations of all three metals in the discharge particulates were substantially higher at SD 7 than at CSO 023, but sediment trap concentrations were higher only for Pb. Based on the relative decreases in metals concentration from outfall to the surface sediments (Table 15), and on their sediment correlations with carbon concentrations (Pb: $r=.920$, Zn: $r=.893$, Cu: $r=.440$), the dispersion hierarchy for SD 7 was determined to be $Pb > Zn > Cu$.

Compared to metals-bearing solids expelled by CSO 023, then, the particles from SD 7 were appreciably smaller overall, with less difference in the relative size and motility of Cu contaminants than for those carrying Pb and Zn. The steeper bathymetry of the SD 7 sampling site also helps aggravate the offshore, near-bottom movement of discharge particulates. Indeed, inspection of the concentration distributions in Figure 25 implies that the sediment enrichment maxima for SD 7 may lie even further offshore.

The surface layer of the bottom sediments at control site C 3 also show signs of contamination by Pb and Zn, with Cu concentrations being similar to those measured in pre-1900 (background) sediments (Table 15). Regression matrices calculated for the C 3 sediments (Table A-2, Appendix) show significant ($\alpha =.01$) correlations for all combinations of C, P, Cu, Zn and Pb (range of $r=.645$ to $.951$) in the 0-0.5 cm layer, whereas no correlations at that level of significance for the 7-8 cm layer. The metals concentrations in the deeper layer were comparable to background levels. Together with the relatively uniform sediment distribution shown by Figure 23, this information implies that the sediments at C 3, one of the "cleanest" areas in the lake, have been contaminanted in recent years by particulates carried thence by longshore advection. This interpretation of the data corresponds to observations made previously relative to the nearshore turbidity assessments. The closest "upstream" outfall is a combined sewer structure located 730 m N of the center of C 3. The dispersion hierarchy determined at C 3 by ranking carbon:metal correlations was Cu > Pb > Zn (r=.951, .927 and .747, respectively); this order was the same as that determined above for CSO 023. There are no shoreline areas in Lake Washington that are more isolated from CSOs or SDs than is control site C 3. It follows from this and from observations of their offshore movement that it is probable that measurable levels of particulate pollutants from CSO and SD discharges cover most of the lake bed.

Typical enrichment factors for total metals contributions from all sources to the top 0.5 cm layer of the nearshore bottom sediments may be derived from data in Table 15, by dividing mean metals concentrations in this surface layer by those for historical (pre-1900) sediments. The resultant values (for Pb, Zn and Cu respectively) are: CSO 023 - 11x, 3x, 2x; SD 7 - 7x, none, 3x; C 3 - 7x, 2x, none. Maximum, near-outfall enrichment can be much greater. As shown by Spyridakis and Barnes (1976), a large portion of the particulate Pb in the lake is of aeolian origin.

Viruses -- Although previous investigators (Smith et al., 1978) have found viruses in sediments using methods identical to those used for the present study, none were detected in surface sediments from either CSO 023 or SD 7. Altogether, 36 separate samples were analyzed, including two sets of six samples taken at the sediment trap locations (Figure 7) within 24 hr of storm overflows, and a third set of six each collected one week after an overflow. The total volumes of the relevant overflows ranged from 415 to 479 m^3 at CSO 023 and 125 to 2230 m^3 at SD 7. The range of recovery efficiences of the internal standards was 8-20%. One set of six samples was also collected at the control site, and likewise yielded no evidence of viruses.

Benthic Biota --

Evaluation of Biological Sampling Techniques -- For purposes of sampling the freshwater benthos, a statistical evaluation of potential techniques was performed, with the number of cores to be collected per placement (by divers) of the 0.5 m^2 wire sampling grid, and the core tube diameter (i.e., sample volume) as variables. The analysis was performed on three of the principal taxonomic groups - chironomids, oligochaetes and copepods. Table 16 shows the upper confidence limits expressed

TABLE 16. UPPER CONFIDENCE LIMITS EXPRESSED AS PERCENTAGES OF THE MEANS FOR 2, 4, 6, 8 AND 10 CORES PER SAMPLING LOCATION FOR CHIRONOMID, OLIGOCHAETE AND COPEPOD COUNTS

		Core Diameter = 29 mm			Core Diameter = 38 mm		
No. of Cores/ Grid	Depth (m)	Chironomids	Oligochaetes	Copepods	Chironomids	Oligochaetes	Copepods
2	1.5	167.6	337.9	325.5	176.1	342.8	580.6
4	1.5	144.1	239.9	230.4	149.3	238.8	349.7
6	1.5	135.9	205.3	197.7	138.5	203.7	279.0
8	1.5	129.6	186.9	180.4	132.8	184.9	243.9
10	1.5	126.2	175.4	169.5	128.8	173.4	222.9
2	4.6	233.1	267.3	706.3	215.4	285.7	586.8
4	4.6	182.4	200.4	405.5	172.4	212.0	352.7
6	4.6	163.2	176.2	316.2	155.9	185.7	281.2
8	4.6	153.1	163.3	272.3	147.0	171.2	245.6
10	4.6	146.3	155.2	245.4	141.2	161.9	223.8
2	7.6	299.0	315.7	340.7	274.7	372.6	279.6
4	7.6	219.3	231.4	242.6	205.7	261.4	206.9
6	7.6	190.6	200.6	207.9	180.6	222.0	181.1
8	7.6	175.4	183.6	189.2	167.1	200.9	167.2
10	7.6	165.4	173.2	177.2	158.4	187.7	158.4

as percentages of the mean total sample counts for each group for a range of numbers of replicate cores; two different core volumes were thusly evaluated. In all cases, the statistical confidence increased with an increasing number of cores per grid placement. With less than six cores taken per placement, however, the confidence decreased substantially. Collecting more than six cores per placement, on the other hand, only slightly increased the confidence. The final sampling was designed for six cores per 0.5 m^2 grid placement, this number representing the best balance of acceptable statistics with minimal cost and effort. Therefore, six cores were collected from each of 12 locations at the control sites, 13 around the SDs and 20 around the CSOs. The sampling locations at the control sites represented varying depths; those around the outfalls represented variations in both depth and distance from the discharge point.

In most cases, the statistical confidence derived from using the 38 mm core tubes was not substantially greater than for the 29 mm tubes. In almost half of the comparisons, the confidence was even greater using the smaller tubes. Since the total amount of sediment (and the relative analytical effort) associated with the 29 mm tubes is only 58% of that affiliated with the 38 mm tubes, the smaller cores were selected for use in the intensive studies.

Abundance and Biomass Comparisons -- The principal objective of this portion of the project was the determination of the extent to which CSO and SD discharges might be affecting benthic organisms in the lake. This was perceived to be a difficult undertaking due to potential concurrent influences of natural factors, including depth, water temperature, currents, light and type of benthic substrate. Of these variables, depth is the most easily measured, and perhaps the most consistent with regard to documented, strong influences on freshwater benthic communities; it was, therefore, used to assess differences between areas in terms of relative number of organisms and biomass, i.e., it was hypothesized that differences in the biota-depth relationships at the outfall sites relative to those determined for the control sites would imply the concurrent influence of other factors, including deposits of CSO and SD particulates. Because depth was found to be relatively constant within the two CSO study areas, only the SD data were examined for depth effects.

It was also hypothesized that any influence of the discharges would demonstrate a linear relationship with distance from an outfall. These relationships were quantified using simple linear regression at the CSOs and multiple regression (with distance and depth as variables) at the SDs. Linear regression techniques were also used to determine the biota-depth correlations for the control sites.

These analyses were done both for the total infaunal community, and for groups of organisms that were either especially numerous in our samples or that are known to be important in the lake's food chains. Included in these categories were chironomid larvae, oligochaetes, nematodes, copepods and pelecypods. A comprehensive summary of the taxa sampled follows:

- Phylum: Arthropoda
  - Class: Insecta
    - Order: Diptera
      - Family: Chironomidae (Tendipedidae; midges)
      - Family: Ceratopogonidae (Heleidae; biting midges)
    - Order: Collembola (springtails)
    - Order: Trichoptera (caddisflies)
    - Order: Ephemeroptera (mayflies)
    - Order: Plecoptera (stoneflies)
  - Class: Arachnoidea
    - Order: Hydracarina (water mites)
  - Class: Crustacea
    - Subclass: Ostracoda (ostracods, seed shrimp)
    - Subclass: Copepoda
      - Order: Eucopepoda (Harpacticoid copepods)
    - Subclass: Malacostraca
      - Order: Mysidacea (mysids)
      - Order: Amphipoda (amphipods)

- Phylum: Annelida
  - Class: Oligochaeta (aquatic earthworms)
  - Class: Hirundinea (leeches)

- Phylum: Oncopoda
  - Class: Tardigrada (water bears)

- Phylum: Platyhelminthes
  - Class: Turbellaria (flatworms)

- Phylum: Nematoda (nematodes)

- Phylum: Coelenterata
  - Class: Hydrozoa (freshwater hydra and jellyfish)

- Phylum: Molusca
  - Class: Gastropoda
    - Order: Pulmonata
      - Family: Planorbidae
        - Genus: *Gyraulus* (freshwater snail)
      - Family: Lymnaeidae
        - Genus: *Lymnaea* (freshwater snail)
  - Class: Pelecypoda
    - Family: Sphaeriidae
      - Genus: *Pisidium* (freshwater mussel)

To compare the relative station-to-station strengths of the depth and distance regressions, coefficients of determination were calculated (C.D. = r^2, where r is the correlation coefficient). These values, presented here in Tables 17-20, represent the proportion of the total variation in organism counts or weights that is explained by each fitted regression.

The correlations are all significant at the 95% confidence level, unless otherwise noted.

Further, plots of the distance regression data were prepared to show the net change in numbers of organisms and biomass per core (means of 6 and 4 cores per site, respectively) as functions of distance from the CSO and SD outfalls (Figure 27). Separate curves were plotted for all significant relationships of the various taxonomic groups for the February and September sampling periods. Because no samples were collected directly at the ends of the storm drain outfalls, those values were estimated by extrapolation.

As judged by the discharge plume turbidity assessments and sediment contaminant distributions, the two CSO stations are more appropriately assessed than are the SDs by the hypothesis that discharge effects are a function of distance from the outfall. Although there are indications that lighter particulates and their associated contaminants may settle in concentrated deposits remote from an outfall, the outfall-surrounding orientation of the CSO sampling arrays is believed to have been reasonably appropriate to the hypothesis. However, because of the on- or near-shore configurations of the SDs, which prohibited anything but semi-circular, offshore sampling arrays, a larger fraction of the discharge particulates bypassed those sampling grids by longshore advection. In addition, there was evidence of substrata differences and physical scouring effects at the near-outfall sampling stations at both SDs. These conditions strongly affected the results of the distance regressions, as described below. With regard to the regressions themselves, the typically low coefficients of determination (r^2) for all stations also reflect the natural patchiness of the benthic communities and the interference of discharge plumes from neighboring outfalls.

Collectively considered, the data summaries offered in Tables 17-20 and Figure 27 serve to define the nature and intensity of the effects of wastewater discharge on the near-outfall biota. Taken station by station, these impacts were determined to be as follows:

CSO 023 -- In order to assess the relationship between the biotic parameters and distance from either CSO outfall, zero distance correlation was assumed for the control sites, implying that any significant correlation determined for a CSO at

TABLE 17. COEFFICIENTS OF DETERMINATION (r^2) FOR LINEAR AND MULTIPLE REGRESSIONS USING TOTAL ORGANISM COUNTS IN FEBRUARY AS THE DEPENDENT VARIABLE

Independent Variable	Taxonomic Group	Sampling Area					
		C3	C4	CSO 023	CSO 044	SD 7	SD 19
Depth	Chironomids	(-).66	(-).61			(-).52	(-).008
	Oligochaetes	(-).50	(-).55			(-).04	(-).04
	Copepods	(-).48	(-).69			(-).15	(-).01
	Nematodes	(-).49	(-).63			(-).37	(-).0004
	Pisidium	(-).0001	.10			(-).21	.07
	Total	(-).66	(-).79			(-).59	(-).002
Distance	Chironomids			.15	.06	NA[a]	.16
	Oligochaetes			(-).56	(-).07	(-).12	.005
	Copepods			.10	.02	.06	.07
	Nematodes			(-).11	.004	(-).27	.20
	Pisidium			.10	(-).01	(-).13	.18
	Total			(-).15	.001	(-).46	.16
Depth+Distance	Chironomids					ND[b]	.28
	Oligochaetes					.16	.09
	Copepods					.18	.14
	Nematodes					.37	.28
	Pisidium					.21	.18
	Total					.59	.25

(a) No association.
(b) Not determined.
Minus signs indicate negative correlation.
Underlined values represent nonsignificant ($\alpha = .05$) correlations.

TABLE 18. COEFFICIENTS OF DETERMINATION (r^2) FOR LINEAR AND MULTIPLE REGRESSIONS USING TOTAL ORGANISM COUNTS IN SEPTEMBER AS THE DEPENDENT VARIABLE

Independent Variable	Taxonomic Group	Sampling Area					
		C3	C4	CSO 023	CSO 044	SD 7	SD 19
Depth	Chironomids	(-).10	(-).01			(-).08	(-).01
	Oligochaetes	(-).71	(-).25			(-).07	.02
	Copepods	(-).19	(-).01			.04	.02
	Nematodes	(-).46	(-).52			(-).10	.001
	Pisidium	.01	.16			NA$^{(a)}$	.11
	Total	(-).48	(-).39			(-).13	.01
Distance	Chironomids			.10	.27	(-).15	.28
	Oligochaetes			(-).0003	(-).39	(-).02	.04
	Copepods			.25	.26	(-).001	.21
	Nematodes			(-).32	.12	.02	.07
	Pisidium			.18	(-).07	(-).15	NA$^{(a)}$
	Total			(-).05	.01	(-).17	.22
Depth+Distance	Chironomids					.16	.43
	Oligochaetes					.07	.04
	Copepods					.13	.22
	Nematodes					.17	.09
	Pisidium					ND$^{(b)}$	.11
	Total					.17	.25

(a) No association.
(b) Not determined.
Minus signs indicate negative correlation.
Underlined values represent nonsignificant ($\alpha = .05$) correlations.

TABLE 19. COEFFICIENTS OF DETERMINATION (r^2) FOR LINEAR AND MULTIPLE REGRESSIONS USING TOTAL ORGANISM WEIGHT IN FEBRUARY AS THE DEPENDENT VARIABLE

Independent Variable	Taxonomic Group	Sampling Area					
		C3	C4	CSO 023	CSO 044	SD 7	SD 19
Depth	Chironomids	(-).17	(-).42			(-).04	(-).04
	Oligochaetes	(-).*01*	(-).*23*			.*001*	(-).*002*
	Copepods						
	Nematodes						
	Pisidium						
	Total	(-).04	(-).36			(-).01	(-).02
Distance	Chironomids			.*06*	.*001*	(-).13	.04
	Oligochaetes			(-).21	(-).*01*	(-).*01*	.*03*
	Copepods						
	Nematodes						
	Pisidium						
	Total			(-).21	(-).*01*	(-).08	.05
Depth+Distance	Chironomids					.18	.15
	Oligochaetes					.*06*	.*06*
	Copepods						
	Nematodes						
	Pisidium						
	Total					.17	.13

Minus signs indicate negative correlation.
Underlined values represent nonsignificant ($\alpha = .05$) correlations.

TABLE 20. COEFFICIENTS OF DETERMINATION (r^2) FOR LINEAR AND MULTIPLE REGRESSIONS USING TOTAL ORGANISM WEIGHT IN SEPTEMBER AS THE DEPENDENT VARIABLE

Independent	Taxonomic	Sampling Area					
Variable	Group	C3	C4	CSO 023	CSO 044	SD 7	SD 19
Depth	Chironomids	(-).15	(-).0002			(-).02	(-).01
	Oligochaetes	(-).08	(-).02			(-).06	.04
	Copepods						
	Nematodes						
	Pisidium						
	Total	(-).21	(-).15			(-).17	.02
Distance	Chironomids			.02	.17	(-).02	.18
	Oligochaetes			(-).01	(-).30	(-).04	.01
	Copepods						
	Nematodes						
	Pisidium						
	Total			(-).04	(-).004	.11	.09
Depth+Distance	Chironomids					.02	.29
	Oligochaetes					.06	.04
	Copepods						
	Nematodes						
	Pisidium						
	Total					.18	.09

Minus signs indicate negative correlation.
Underlined values represent nonsignificant ($\alpha = .05$) correlations.

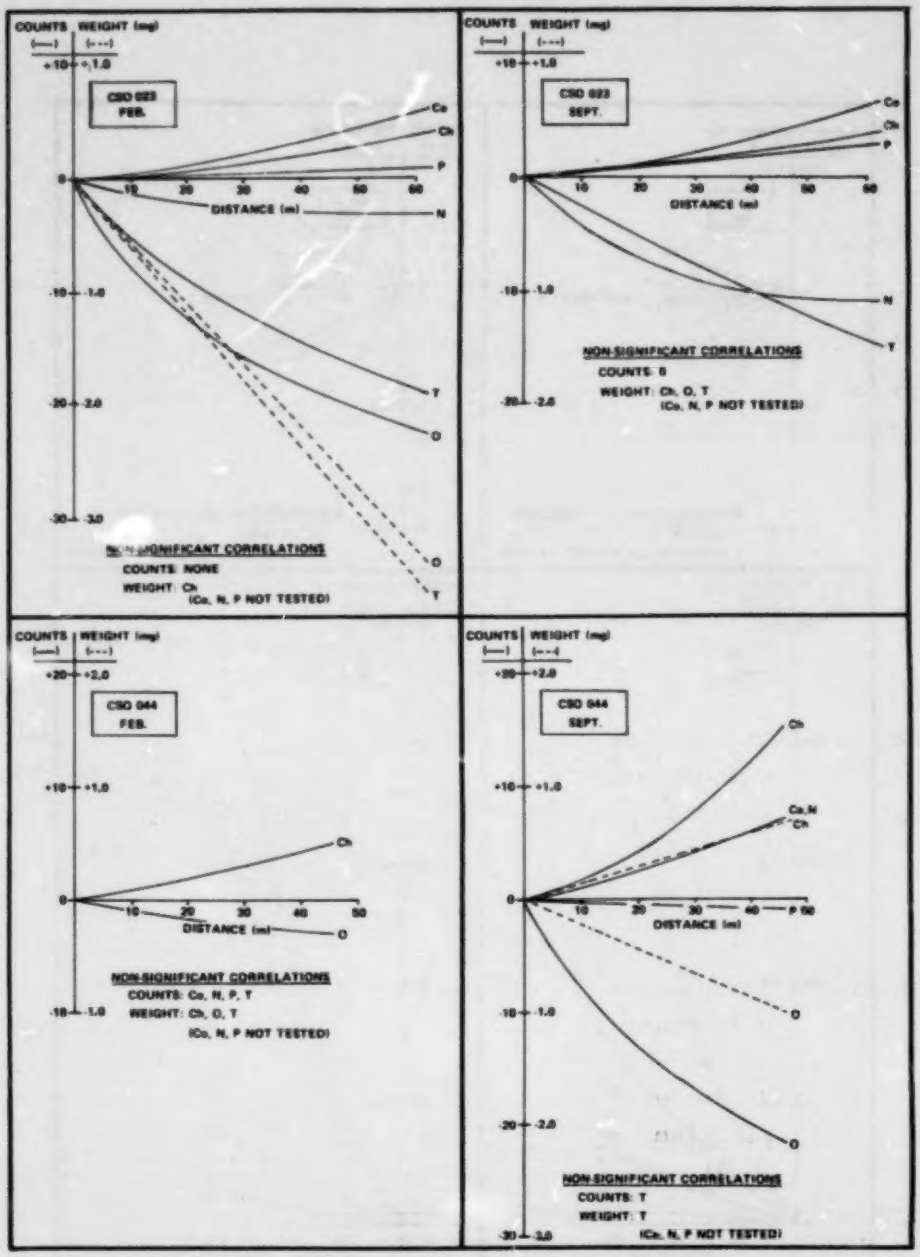


Figure 27. Net change in numbers of organisms and biomass per core, as a function of distance from the combined sewer and storm drain outfalls in February and September, 1978. All relationships determined by regression analysis and significant (at the 95% confidence level) unless otherwise noted. Ch: chironomids, O: oligochaetes, Co: copepods, N: nematodes, P: pelecypods (Pisidium spp.), T: total for all organisms.

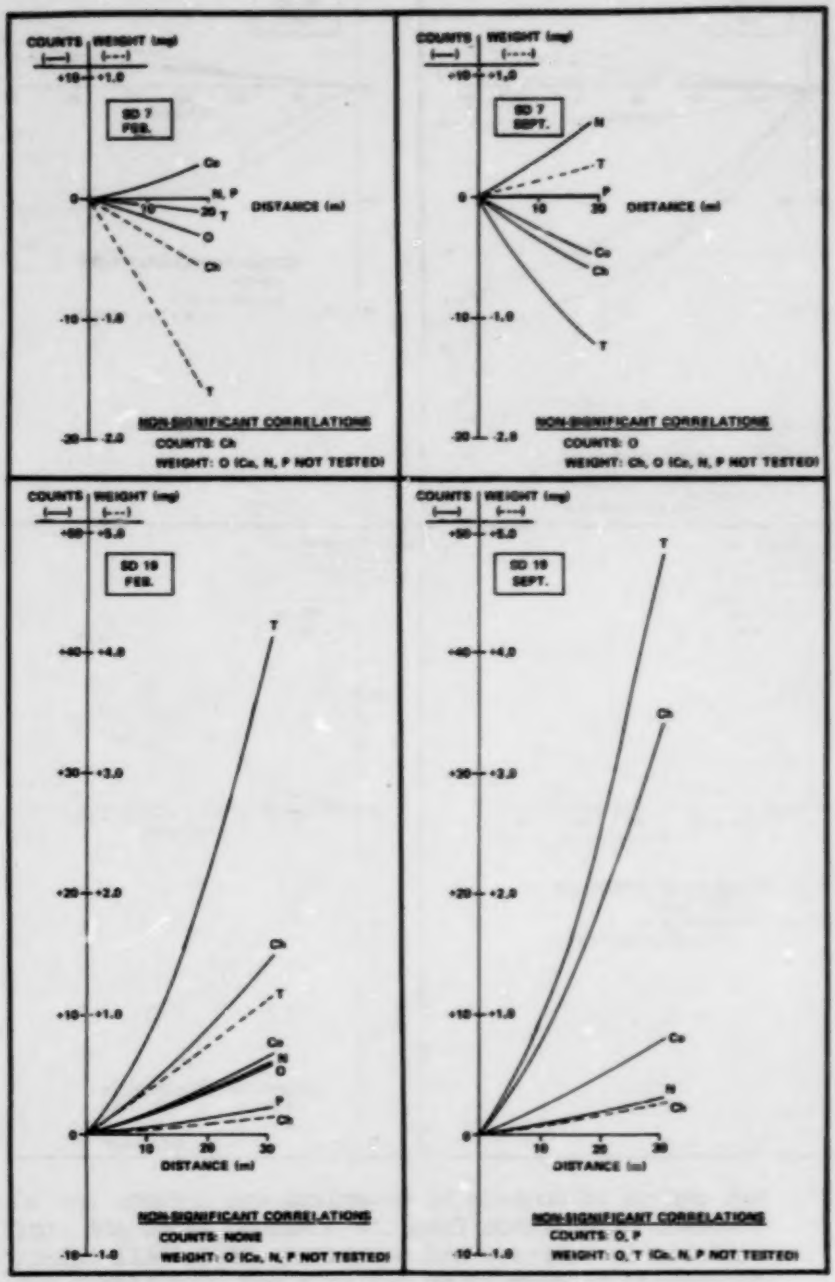


Figure 27. (continued)

constant depth was due to the presence of the outfall. With reference to Figure 27, the strongest distance relationships determined for CSO 023 were those for the oligochaetes (aquatic earthworms) in February and the nematodes (roundworms) in September. The correlations in each case were negative, suggesting population enhancement near the outfall; these data reinforce the commonly noted association of detritus-feeding aquatic worms with sediment deposits rich in organic pollutants (Hart and Fuller, 1974; Wetzel, 1975). The total population of both oligochaetes and nematodes was seen to increase during the dry season, when warm weather stimulates feeding and reproductive activity (Wetzel, 1975). The principal difference between the two taxonomic groupings was that, in general, the February-to-September increases for oligochaetes occurred away from the outfall, whereas those for nematodes occurred near the outfall, with the residual population in each instance remaining essentially constant; the reasons for this difference are unknown, but may relate to feeding competition or a differential response to toxicants or substrate alterations. Oligochaetes and nematodes dictated the total population correlations in February and September, respectively.

Figure 27 also shows a weak positive relationship at CSO 023 between distance from the outfall and the numbers of chironomid (insect) larvae, copepods (microcrustaceans) and pelecypods (mussels). These correlations, which were non-seasonal in terms of magnitude, imply that the CSO discharges may have been slightly toxic to these populations. Smothering by settling particulates may also have contributed to the observed decreases

CSO 044 -- As for CSO 023 in February, there were negative correlations of numbers of oligochaetes with distance from the CSO 044 outfall during both seasons. The fraction of the total oligochaete population found in the visible discharge debris near the outfall (representing 55% of the samples taken) was 68-73% for all three data sets, indicating enhancement by the organic effluent (refer to Figure 4 for sampling array configurations). The reason for the lack of similar correlations at the two CSOs in September is not clear, but may be a result of inter-specific differences in toxicity tolerance.

The only other relationship that was consistent between CSO 023 and CSO 044 was the positive correlation with distance of numbers of chironomids, during both seasons. The fraction of these organisms in the outfall debris (half of the samples) ranged from 23% to 36% for the two outfalls during the two seasons. This numerial depletion near the outfalls probably represents a reaction to toxic substances or substrate alterations in the near-outfall deposits.

As opposed to the data reviewed for CSO 023, the copepods and nematodes showed no significant response to discharge from CSO 044 during February, and the nematodes had a reversal of correlations during September. Noting that only positive relationships between nematode counts and distance from the outfall were seen at CSO 044, SD 7 and SD 19, the negative response determined for both seasons at CSO 023 constitutes an anomaly with no obvious explanation.

It is of interest to note that count and weight measurements for the total population of benthic infauna at CSO 044 show no net correlation with distance from the outfall. For both seasons tested, the positive and negative relationships noted for the various taxonomic groupings were collectively nullifying in algebraic summation. It is apparent that the information to be derived from measurements of the total population is potentially misleading.

SD 7 -- Correlations with both distance from the outfall and depth were also calculated for numbers of infaunal organisms and biomass determined for the two storm drains, SD 7 and SD 19. For reasons mentioned previously, i.e., localized substrate differences, near-outfall scouring effects, and the relatively poor juxtaposition of the discharge plumes with the sampling arrays, this information (Tables 17-20 and Figure 27) must be interpreted with care. The substrate and scouring problems had the most obvious impact on the statistical results. These effects reduced the number of organisms found at the sampling site closest to the terminus of each outfall. These aberrations in turn influenced the slopes of the counts vs distance and weight vs distance relationships by intensifying the positive correlations and weakening the negative ones. Accordingly, further interpretations of these relationships were supplemented by an inspection of the raw data. Compared to the coefficients of determination calculated for the two control sites, the values derived for both of the storm drains indicate an "unnatural" moderation of the strength of the counts vs depth and weight vs depth relationships. Whereas the controls had a statistically strong increase in numbers and biomass with decreasing depth, these relationships were less definite at the storm drains; as detailed below, this is likely due to the physical coincidence of decreasing depth with increasing proximity to the outfall and the influence of its associated discharge particulates.

Collectively, the available evidence for the distance relationships (including an inspection of the raw data to identify and compensate for the aforementioned scouring impacts) indicates the following, which differs in a few instances with the picture presented by Figure 27 and the statistics given in Tables 17-20: the numbers of chironomids and oligochaetes were moderately enhanced by the discharge (negatively correlated with distance from the outfall) in both February and September; the effect for copepods and nematodes was less definite, with copepod enhancement in September being the most definitively indicated relationship (based on the raw data); the pelecypod correlations for both seasons showed no notable distance relationships. Of these, the trends denoted for oligochaetes agreed with those at the CSOs, but enhancement of chironomids and copepods was distinctly different from the depletion effect associated with the combined wastewater systems. Based on the present analysis, however, the trend disagreement was lacking statistical verification. There was no apparent difference in the mean concentrations or loading of the discharge constituents at these stations (Tables 5 and 8) that would explain this observation.

SD 19 -- The data trends for SD 19 were much stronger than those at SD 7 and the final observations based on both the raw data and the statistical analyses vary only slightly from the summary depicted by Figure 27 and Tables 17-20. The single apparent change is for numbers of oligochaetes, which were in fact enhanced by the discharge during both seasons, except directly in front of the outfall, where there was a nontypical sand substrate. This material was probably from the outfall and in itself constitutes a localized discharge impact that reduced the infaunal population at that site. This effect was contrary to the overall areal trend only for oligochaetes. All other populations tested showed definite evidence of depletion near the outfall.

Summary -- The general trends observed with respect to wastewater impacts on the benthic infauna near the four outfalls indicated enhancement of oligochaetes (aquatic earthworms) at all sites. The greatest enrichment of the worm population occurred at the CSO sites, probably due to the "predigested" (in human guts) nature of the particulate carbon of the discharge, a mixture typically rich in carbohydrates, proteinaceous compounds, fatty acids and other substances more readily degraded by microorganisms, which in turn are the principal food source of the oligochaetes. By contrast, the SDs emit principally humic substances, partially degraded plant material that is more resistant to microbial degredation, and tends to persist as particulates with relatively long residence times. Decremental impacts, attributed to discharge toxicity, substrate alterations and/or smothering by particulates, were determined for chironomids (aquatic insect larvae) at CSO 023, CSO 044 and SD 19; the chironomid trends for SD 7 were somewhat obscured by aberrant patches of substrate, but appeared to indicate near-outfall enhancement during both seasons. At CSO 023, CSO 044 and SD 19, the populations of chironomids remained essentially constant near the outfalls from February to September. During the same period, the numbers of these organisms further away increased substantially, indicating a reduction in community stress concomitant with the seasonal decrease in discharge.

These observations for chironomids imply that the area of visible debris accumulation around an outfall exerts a detrimental influence the year around on some organisms. Although it does not strictly constitute a dead zone, the numbers of individuals of its sensitive resident species are depressed and invariate relative to ambient conditions. The net seasonal change in numbers from reproduction, mortality and recruitment is minimal. Outside of this zone of maximum deposition lies a region that may be seasonally influenced by the discharges; there, the potential for a rapid return of the affected species to ambient levels is much greater. Strictly speaking, with additional data the linear and log-linear relationships of Figure 27 might be revised to include a slope break to define the two zones of influence.

Copepods (Harpacticoida, i.e. benthic microcrustaceans) also seemed to be negatively impacted by discharges from CSO 023, CSO 044 and SD 19. The general tendency at these stations was for the copepod populations to decrease between the wet and dry seasons, perhaps on response to natural cycles. However, in each instance the seasonal decreases observed within the discharge debris were appreciably greater than those outside of it (SD 19 experienced copecod population increases away from the outfall). The net effect of these changes between February and September was to intensify the positive correlation of numbers vs. distance from each outfall. A clear interpretation of the more specific nature of the discharge impacts relative to these concurrent phenomena was not apparent. As was observed for the chironomid populations, the trends for seasonal changes of numbers of copepods were unusual at SD 7, perhaps due to losses from near-outfall scouring.

The tendencies noted for the communities of nematodes (roundworms) near the outfalls were extremely variable, ranging from significantly positive at SD 19 in February to significantly negative at CSO 023 in September. The variable response of nematodes to discharges may be due to a wide range of species tolerances to the particulate toxicants. In general, the numbers of pelecypods (freshwater mussels) varied little and unsystematically with distance from the outfall, from one station to the next.

MARINE STUDIES

Discharge Monitoring

Discharge Loading Estimates for Single Events -- The CSO discharges generated by two storm events were sampled quantitatively and qualitatively at the Denny Way Regulator in order to determine typical particulate inputs to marine waters by a large combined sewer outfall. Table 21 is a summary of the storms monitored.

TABLE 21. SUMMARY OF RAINSTORMS MONITORED FOR QUANTITY AND QUALITY OF DISCHARGES INTO PUGET SOUND FROM THE DENNY WAY REGULATOR OUTFALL, MARCH AND OCTOBER, 1978

Date	Total Rainfall (cm)	Overflow Duration (hr)	Discharge Volume (m^3)	Discharge Fraction[(a)] (%)
3/7	3.20	6.3	20730	29.1
10/23-10/24	0.53	3.7	12010	102

(a) The volume fraction of the total basin-incident rainfall that was discharged by the outfall during the period noted.

Further, a statistical summary of the resultant contaminant mass discharges is offered in Table 22. Relative to the comparable data compiled for the freshwater study sites, the total storm loading of each pollutant discharged by the Denny Way outfall was much greater, due to its larger discharge volumes. Only the mean concentrations of suspended solids, total Hg and total P at Denny Way were similar to those of the other combined facility, CSO 023. The mean total and particulate Cu, Pb and Zn concentrations at Denny Way were higher than those of either of the freshwater stations, reflecting its large component of industrial and commercial inputs (34% by land area). The mean concentration of particulate chlorinated hydrocarbons at Denny Way was only a small fraction of the concentrations measured at the two Lake Washington sites, implicating residential use of pesticides as the principal source.

Rainfall, Flow and Loading Summary -- As mentioned previously, the total measured rainfall for the Denny Way station was 98.8 cm for the one year study period. This was just slightly more than a 30-year annual mean published for the same area by Phillips (1968). The rainfall pattern and the resultant overflow response by the Denny Way

TABLE 22. STATISTICAL SUMMARY OF ESTIMATED POLLUTANT LOADS AND CONCENTRATIONS IN STORM DISCHARGES MONITORED AT THE DENNY WAY REGULATOR, MARCH AND OCTOBER, 1978

MASS RANGE:	kg	No. of Storms
Suspended Solids	1960 - 2120	(2)
Total Cu	.954 - 1.56	(2)
Total Hg	.0073 - .0135	(2)
Total Pb	5.45 - 6.78	(2)
Total Zn	4.40 - 4.63	(2)
Total Al	54.4	(1)
Total Organic C	432	(1)
Total P	17.1 - 21.7	(2)
Total O & G	204 - 310	(2)
Particulate ClHC	1.25 - 120 mg	(2)

MEAN PARTICULATE MASS:	Percent(a) of Total Mass	No. of Storms
Suspended Solids	100.0	(2)
Cu	72.1 ± 0.4	(2)
Hg	70.6 ± 6.0	(2)
Pb	92.7 ± 4.1	(2)
Zn	54.6 ± 20.0	(2)
Al	94.9	(1)
Organic C	55.6	(1)
P	48.7 ± 13.4	(2)
O & G	NA(b)	
ClHC	ND(c)	

MEAN DISCHARGE CONCENTRATION:	(mg/l)	Range of 1σ
Suspended Solids	129	92.4 - 181
Total Cu	.077	.074 - .080
Total Hg	.0006	.0006 - .0007
Total Pb	.385	.306 - .486
Total Zn	.285	.187 - .437
Total Al	2.62	ND
Total Organic C	20.8	ND
Total P	1.23	.985 - 1.52
Total O & G	16.0	14.6 - 17.4
Particulate ClHC	.001 ppb	.000 - .013

(a) $\bar{x} \pm 1\sigma$
(b) Not applicable.
(c) Not determined.

system is shown in Figure 28. For a total of 59 periods of measurable rainfall (separated by one or more dry days), there were 36 controlled overflows at Denny Way. Taking into account the fact that multiple overflows occurred during some of the long storms, the fraction of storms resulting in overflows was 51%; the average total rainfall for those storms that failed to generate overflows was .25 cm.

The total overflow volume for the 12-month monitoring period was 6.60 x $10^5 m^3$ (175 MG). In combination with the mean discharge concentrations given in Table 22, this value was used to calculate total annual loads for the various parameters of interest. The results are presented here in Table 23. With the exception of chlorinated hydrocarbons, the loading for all parameters at Denny Way was much greater than at CSO 023 and SD 7, due to its greater total volume of overflow.

TABLE 23. ESTIMATED MASS OF SELECTED CONSTITUENTS IN DISCHARGES FROM THE DENNY WAY REGULATOR OUTFALL, MARCH 3, 1978--FEBRUARY 28, 1979

	Total Mass (kg)	Particulate Mass (kg)
Suspended solids	85100	85100
Cu	50.8	36.6
Hg	.396	.280
Pb	254	236
Zn	188	103
Al	1730	1640
Organic C	13700	7630
Total P	812	395
O&G	10600	NA(a)
ClHC(b)	ND(c)	.660g

(a) Not applicable.
(b) Selected chlorinated hydrocarbons: α-BHC, lindane, heptachlor, heptachlor E, aldrin, dieldrin, endrin and DDT (DDD + DDE + o,p DDT + p,p DDT).
(c) Not determined.

Turbidity Distributions of Discharge Plumes

The distributions and movements of wastewater discharge plumes were monitored near the Denny Way outfall during storms on April 15-16, 1978 and February 24-25, 1979. The relative rainfall, total overflow volumes and tidal variations are given in Table 24.

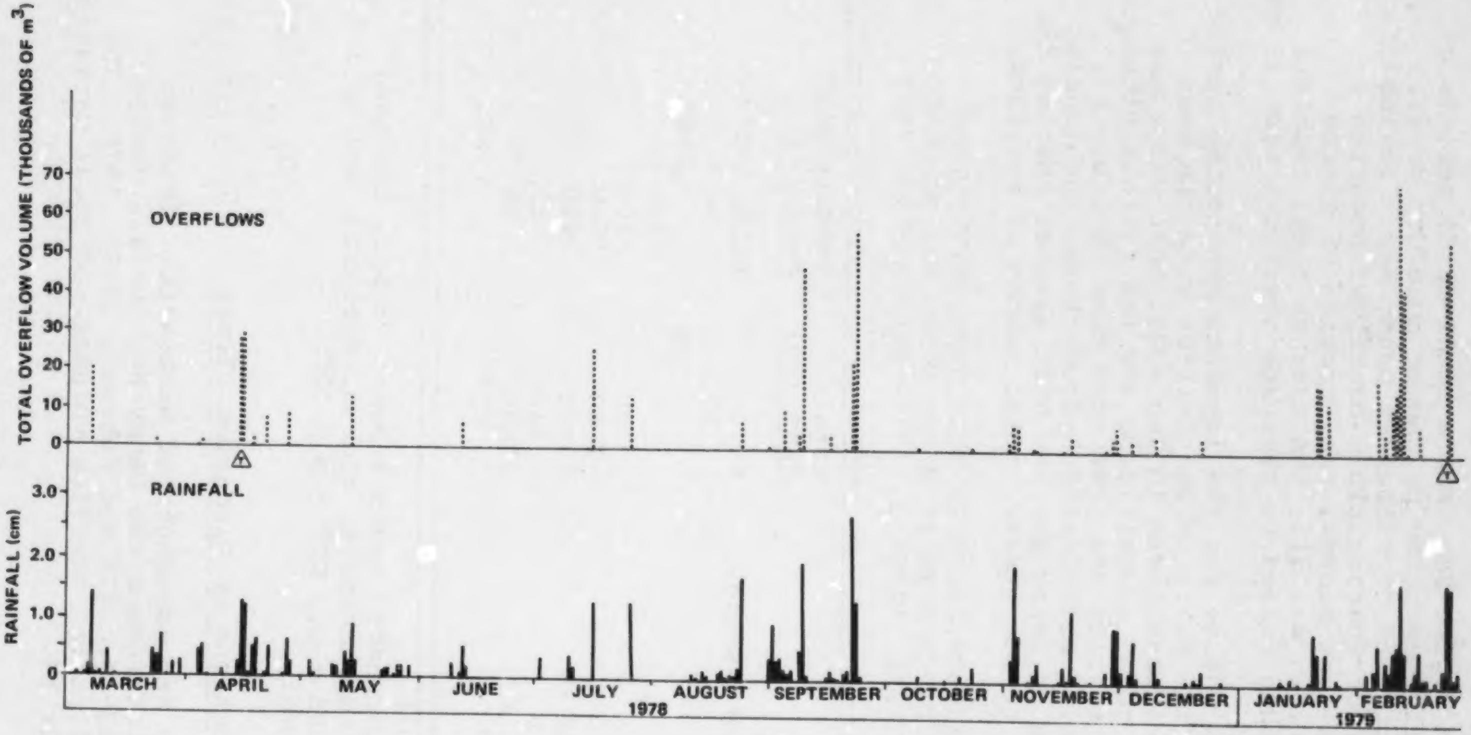


Figure 28. Summary of rainfall and overflow response at the Denny Way Regulator outfall from March 1978 to February 1979. The triangle symbols designate storms monitored for discharge turbidity distributions.

TABLE 24. RAINFALL, OVERFLOW VOLUMES AND TIDAL VARIATIONS FOR OVERFLOW TURBIDITY DISTRIBUTIONS MONITORED AROUND THE DENNY WAY REGULATOR OUTFALL, APRIL 1978 AND FEBRUARY 1979

	April, 1978			February, 1979	
	15	16	17	24	25
Total Rainfall	4.98 cm			5.18 cm	
Overflow Volume	56900 m^3			48100 m^3	
Overflow Times	1728 - 1210			1322 - 0122	
Monitoring Times		0517-0746	1254-1530	2050-2243	0555-0755
Tide Time/Height(a)		0013/3.1	0105/3.2	0339/3.6	0417/3.7
	0502/2.0	0618/1.8	0717/1.6	0902/1.9	0952/1.6
	0901/2.5	1057/2.4	1216/2.4	1409/3.3	1510/3.4
	1640/0.6	1742/0.7	1841/0.8	2112/-0.4	1158/-0.4

(a) In meters, relative to MLLW

As can be determined from these data, the most significant differences between the two storms monitored are the strength and number of tidal excursions associated with the overflows prior to sampling, and the fact that the second 1978 sampling was done post-storm, whereas that in 1979 was carried out during the storm. All of the other important statistics are similar for the two storms including the portions of the tidal cycle sampled (low slack and ebb).

Interpretation of the Denny Way turbidity data was much more difficult than were those collected previously in Lake Washington. This was due to massive background interference from the Duwamish River to the south (see Figure 2 for location perspective). During substantial rainstorms the river flow increases appreciably; as such, it is highly visible as a muddy surface layer, 1.5-3.0 m thick, and as much 1000 m wide (extending from the northeastern shore to the middle of Elliott Bay) and moving along the shoreline through the designated sampling area and northward around West Point. The boundaries of this feature were verified during the present project with light transmission measurements made along transects extending more than one mile offshore into Elliott Bay.

The collective influence of the river and the tidal strength and direction can be seen in Figures 29 and 30 (refer to freshwater section for a discussion of turbidity monitoring

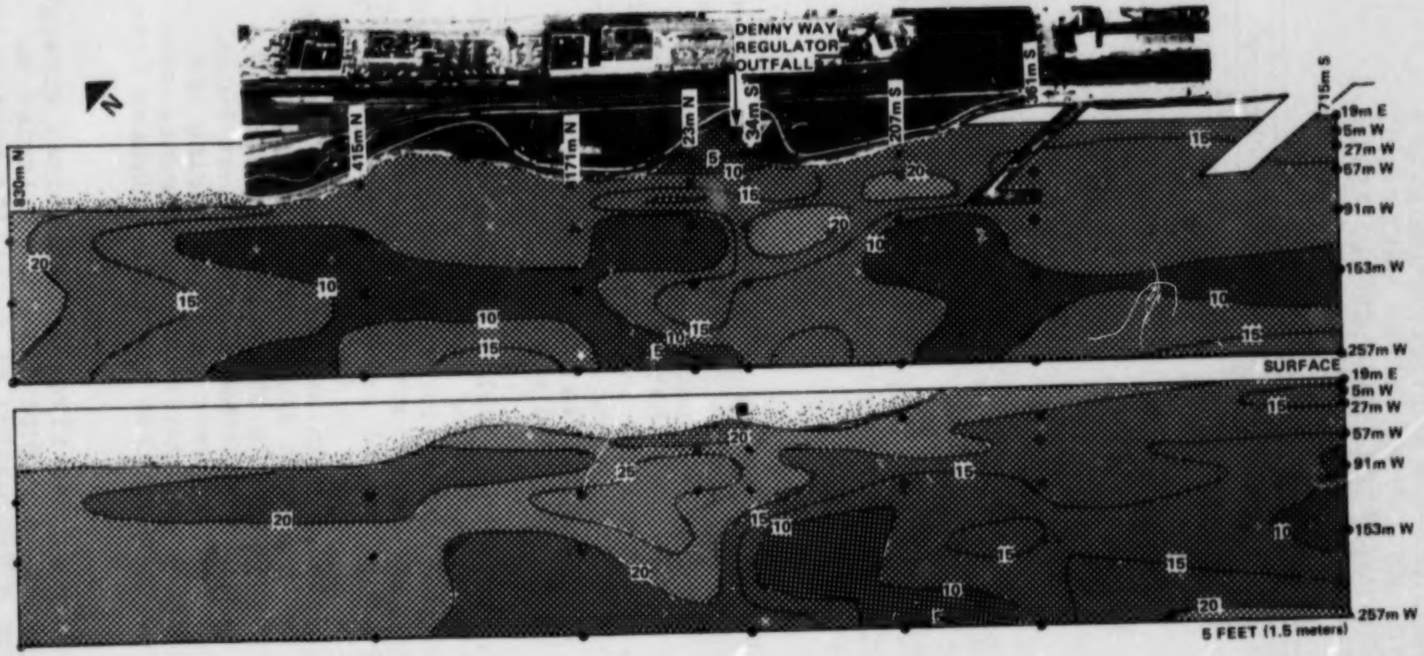

DENNY WAY
REGULATOR
OUTFALL
930m N
415m N
171m N
23m N
34m S
207m S
361m S
715m S
19m E
5m W
27m W
57m W
91m W
153m W
257m W
SURFACE
5 FEET (1.5 meters)
N
5
10
15
20
25

Figure 29. Aerial perspectives of contours of percent light transmission around the overflow outfall of the Denny Way Regulator--0517-0746 hrs., 4/16/78.

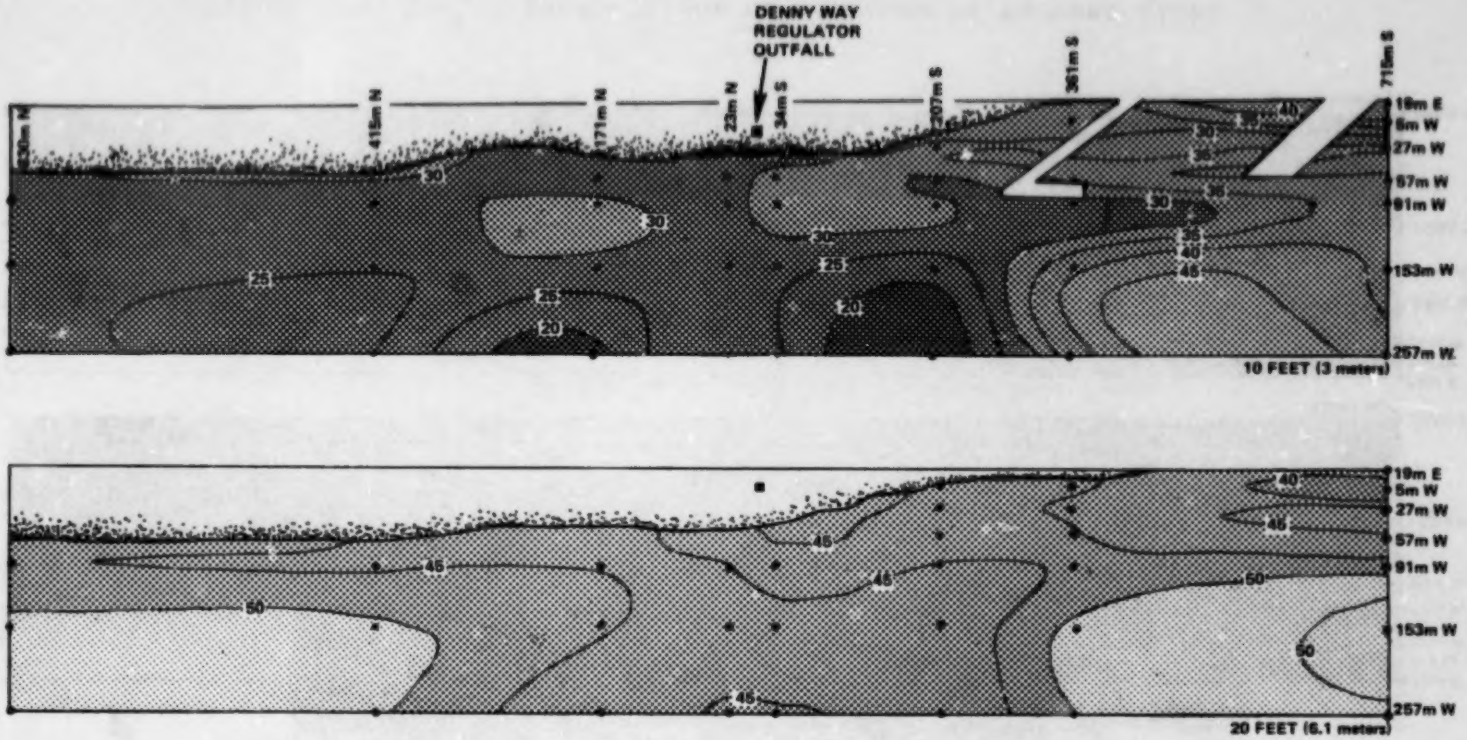

DENNY WAY
REGULATOR
OUTFALL
415m N
171m N
23m N
34m S
207m S
361m S
715m S
19m E
5m W
27m W
57m W
91m W
153m W
257m W
10 FEET (3 meters)
20 FEET (6.1 meters)
20
25
30
35
40
45
50

Figure 29. (continued)

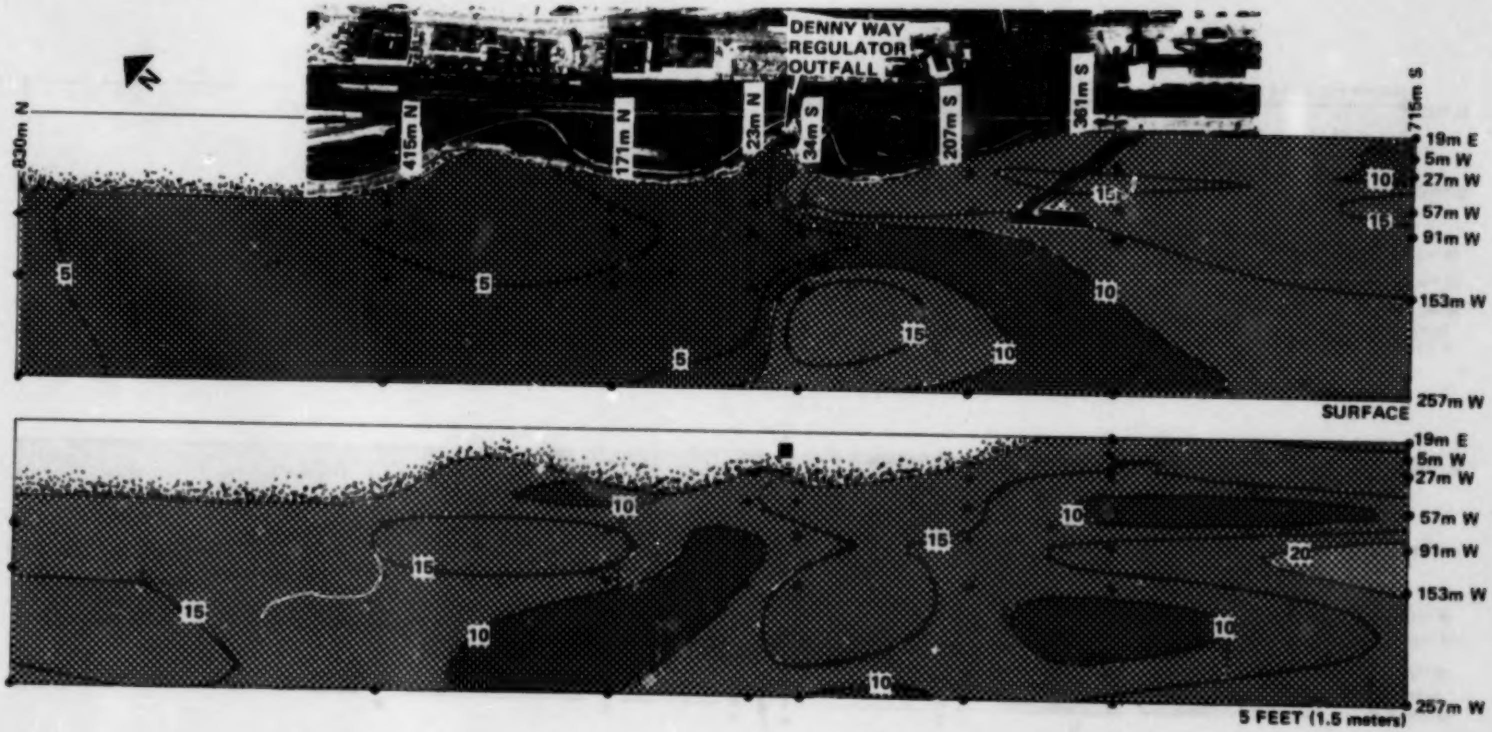

DENNY WAY
REGULATOR
OUTFALL
830m N
415m N
171m N
23m N
34m S
207m S
361m S
715m S
19m E
5m W
27m W
57m W
91m W
153m W
257m W
SURFACE
5 FEET (1.5 meters)
5
10
15
20
N

Figure 30. Aerial perspectives of contours of percent light transmission around the overflow outfall of the Denny Way Regulator--2050-2243 hrs., 2/24/79.

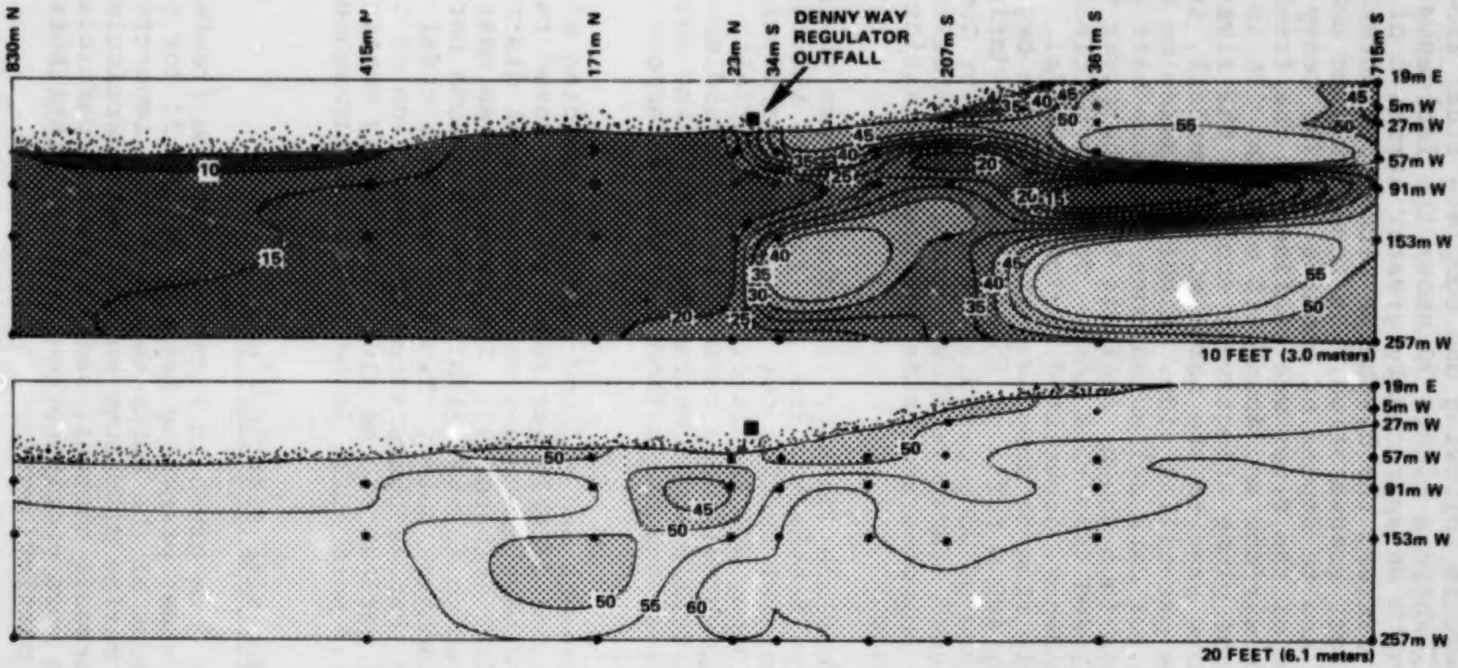


Figure 30. (continued)

theory). Figure 29 depicts light transmission distributions in the surface waters following one complete tidal flood and ebb during overflow, whereas Figure 30 shows the influence of an ebb tide only, with an appreciably greater strength of flow. As shown by the latter, the discharge plume, characterized by low values of light transmission, was found only to the north of the outfall, and to depths of about 6 m. The heavy particulate load of the river was confined to the freshwater lens between the surface and about 4.5 m depth. It is apparent that the discharge plume effectively excluded the river water from the nearshore area to the north of the outfall, in the direction of the prevailing tide. Light transmission distributions plotted for data collected more than one half of a tidal cycle later (not shown) indicate that the river flow was still being excluded from this area. This was partially due to a natural tendency, documented by Tomlinson et al. (1976), for the northerly flow to move away from the shore beginning at approximately 400 m north of the outfall, even during fair weather. Evidence of eddy circulation also seen by Tomlinson et al., that caused nearshore flow counter to prevailing tidal flow, was not observed under the storm conditions of the present project.

The intense pycnocline (density gradient) between the saltwater and the overlying freshwater from the river and the outfall constitutes a natural barrier for the sinking particulates emitted by the Denny Way Regulator's onshore outfall. Whereas this feature undoubtedly does reduce the local sedimentation rate, its perturbation and penetration by settling solids is evident in vertical onshore-offshore transects across the plume (Figure 31).

Following both an ebb and a flood tide, the leading edge of the discharge plume for 4/16/78 was found to have moved further offshore, and to have assumed a more symmetrical distribution around the outfall (Figure 29). The general area most heavily impacted appeared to be that within 200-300 m both north and south of the discharge point. Two and one half tidal cycles later, and more than 24 hours after the cessation of overflow, large, residual patches of the plume (one being contiguous with the outfall) were still found scattered throughout the study area.

Sediment Particle Size Distributions

Compared to the data given in Figure 23 for the freshwater stations, the values presented here in Figure 32 for particle size distributions at the Denny Way site show important differences. The marine discharge and sediment particulates had a much higher organic content, smaller medium particle diameters, were more poorly sorted, and had distributions favoring finer particulates.

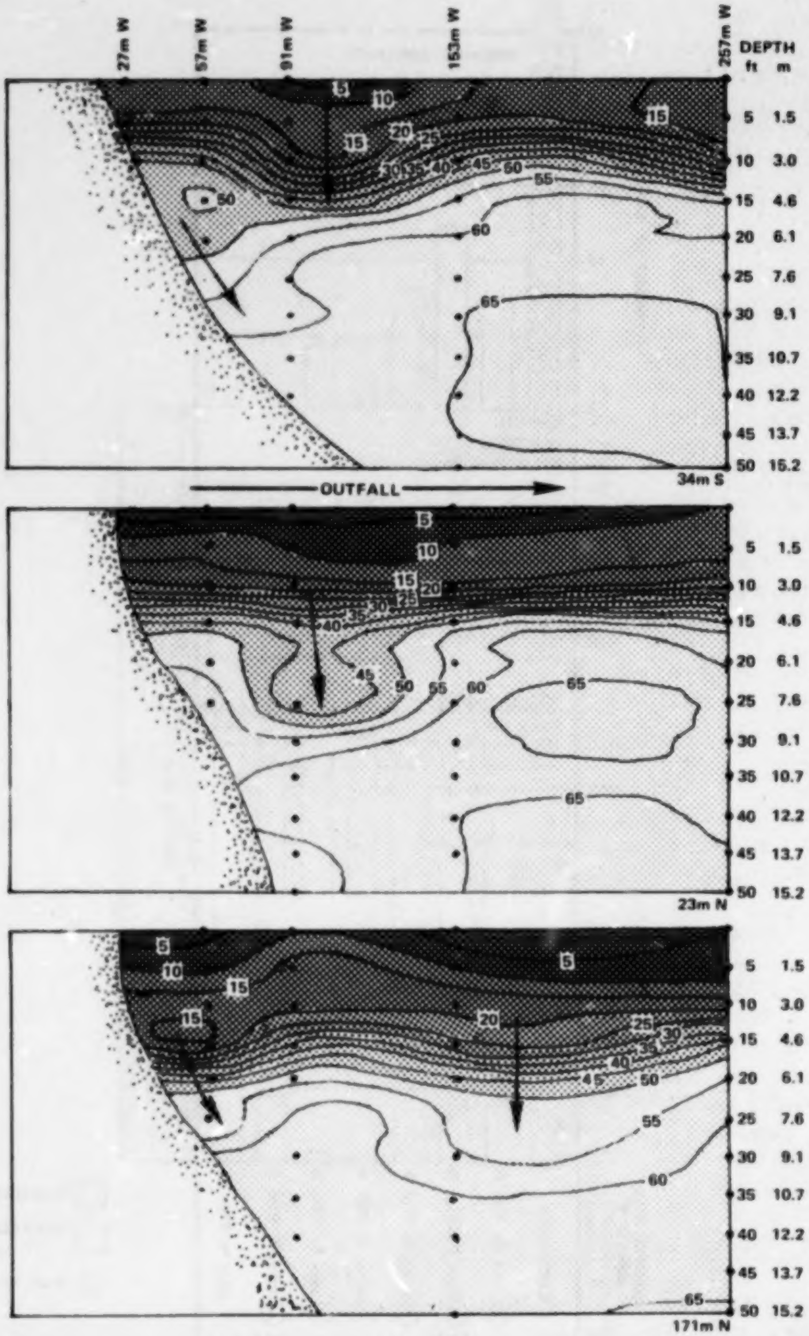


Figure 31. Transverse sections of contours of percent light transmission around the overflow outfall of the Denny Way Regulator— 2050-2243 hrs., 2/24/79. The perspective is that of a diver looking south along the shoreline with Elliott Bay to his right. The arrows indicate areas of particulate settling.

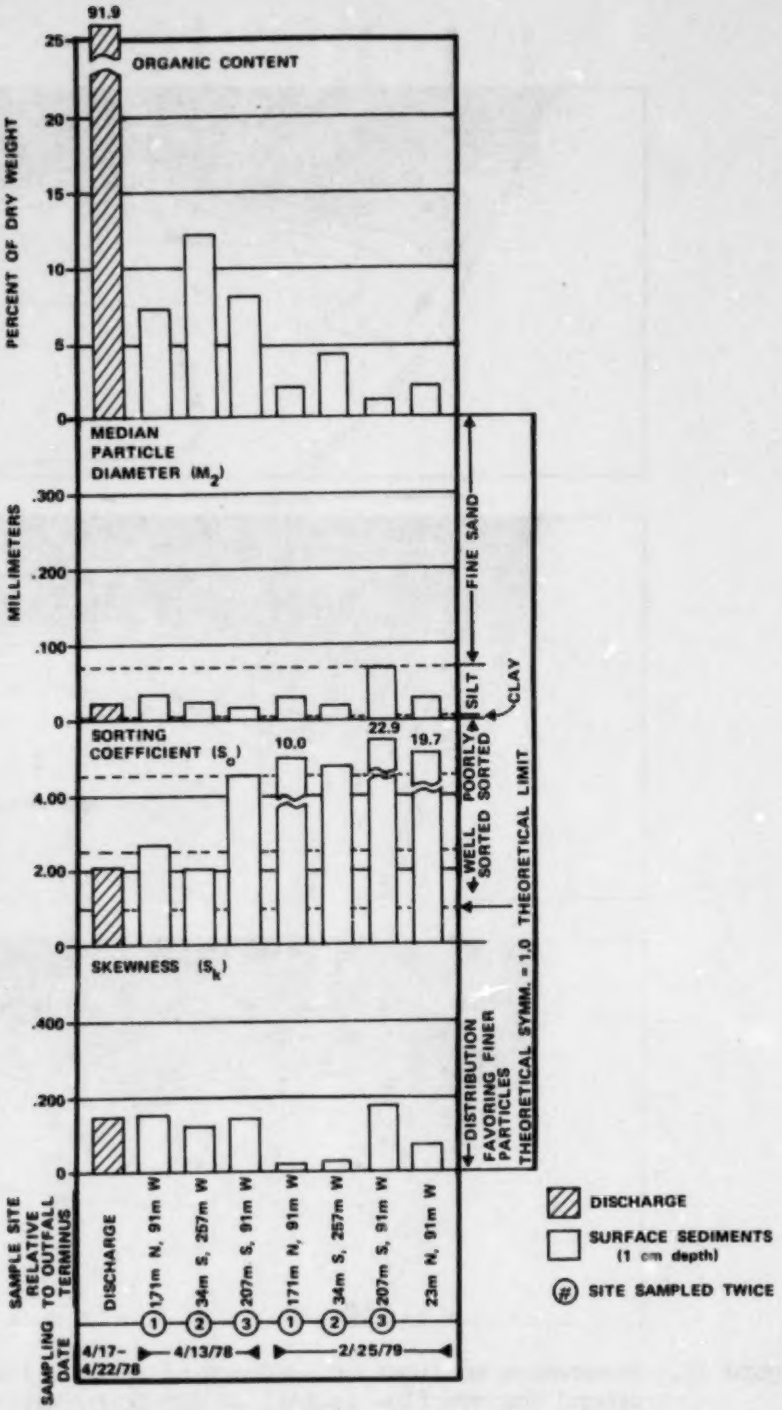


Figure 32. Summary of particle size distribution analyses for the Denny Way Regulator.

Considering the extremely high discharge organic content at Denny Way, and the 0% to 3% background measurements obtained in conjunction with the biological studies, it seems apparent that the three sediment samples collected in April showed organic enrichment by discharged particulates. The poorly sorted sample from 207 m S, 91 m W of the outfall seems to have been influenced by the turbulence generated by tidal action around Pier 71. This observation is further corroborated by data. Together, these data constitute evidence that piers can influence the settling characteristics of discharge particulates; a phenomenon also observed near CSO 023 in Lake Washington, as mentioned previously. The fact that the CSO and SD particulates analyzed for the freshwater stations were more poorly sorted (i.e., a larger range of particulate sizes were intermixed) than those emanating from the Denny Way facility would seem to indicate a greater tendency for settling (a sorting process) within the latter system.

Three of the sites sampled near the Denny Way Regulator were sampled twice for purposes of seasonal comparison. The April, 1978 set was collected after a week of almost negligible precipitation, whereas the February, 1979 sampling was done toward the end of a storm that totalled 5.18 cm of rain and caused an overflow of 48100 m^3 (12.7 MG). The differences in the nearshore surface sediments under these two sets of conditions is quite graphic. As shown by Figure 32, the sediments collected following the large storm overflow had an appreciably lower organic content due to dilution of the particulate sanitary wastes with large quantities of inorganic particulates carried into the system by storm runoff. These more dynamic flow conditions also resulted in a much more poorly sorted sediment surface layer.

Benthic Biota

The number, volume and rate of flow of overflows were appreciably greater during the time prior to the first sampling (during April, 1978) as compared to the time prior to the second (during August, 1978) (Figure 28). Most overflows occurred when the conduit was at least partially submerged. Therefore, the discharge usually underwent immediate dilution. The "wash out" zone was evident, however, indicating that scouring was taking place.

Mollusc Bioassays--

Condition Index -- The condition index (CI) of bivalves is a measure of the "plumpness" of the soft tissue and can be used to indicate the health of a population of these organisms. The results of the in situ bivalve bioassay done for this project showed that reproduction had the most significant effect on condition index (Figure 33). Mussels in all test pots contained large numbers of eggs in April. A marked decline in CI after

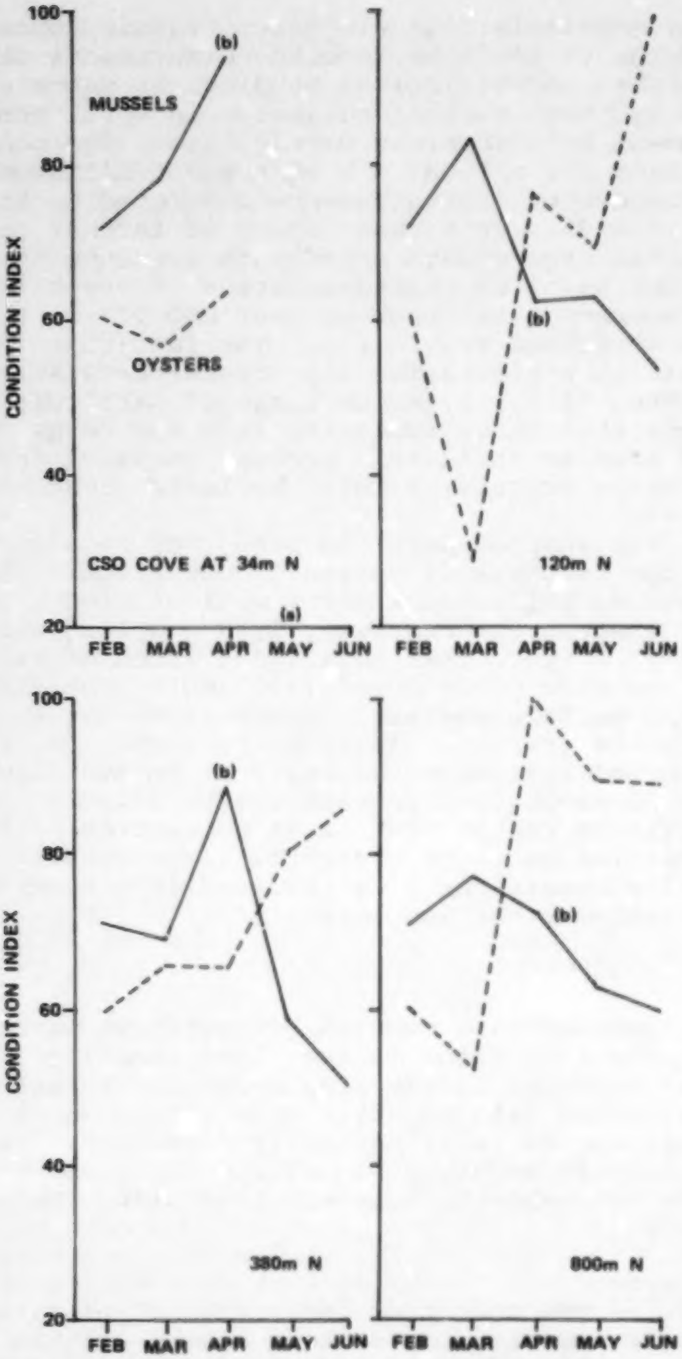


Figure 33. Variation in the condition indices of mussels and oysters kept in pots at four sites near the Denny Way Regulator outfall. (a) pot lost; (b) reproductive condition.

that month was related to a characteristic decline in "plumpness" of the test organisms associated with liberation of eggs. There was no discernable increase or decrease in the CI of oysters as a function of distance from the CSO; this suggests that the CSO had no significant effect on the health of these organisms. The experiments were terminated after approximately four months due to the loss of all pots (through storms or theft) except the one at 800 m N of the outfall.

The present results differ from those of a previous study at Denny Way (Armstrong et al., 1978). Armstrong et al. did see a decrease in CI with decreasing distance from the CSO. The organisms apparently did not reproduce during their study period, however, and this may account for the differing results. The organisms available for use in the present study had a lower initial CI than those used by Armstrong et al. It may be that, if the organisms had had a higher initial CI, a drop in CI could have been detected.

Uptake of Metals -- The heavy metal content of the meat of mussels changed over the 10 weeks of exposure (Table 25). The net increase in the concentrations of Cu and Pb was greatest in the mussels closest to the CSO and decreased with distance from the CSO. Zn concentrations decreased in mussel tissues at all sites. The values for Cu and Pb were within the range of values reported by Manly and George (1977) for the freshwater mussel *Anodonta anatina* in polluted urban areas in Great Britain. The Cu concentration found in mussels near the Denny Way CSO was somewhat lower than the concentration in the same species in polluted areas in southern California (Young and Alexander, 1977). The Pb content was higher near the CSO than in southern California, however. Similar to the present study, Young and Alexander found that Zn appeared not to be taken up by the mussels.

Lead concentrations in oyster meats appeared to be related to proximity to the CSO (Table 26). There are no data readily available from other geographic areas with which to make comparisons.

Effects of Discharge on Algal Morphology -- Samples taken in April showed that the ratio of *Enteromorpha* blade width to unit length decreased with increasing distance from the CSO (Figure 34). This relationship was essentially reversed in August. The difference between the results may be related to the decline in number of overflows in summer. There is no clear explanation evident either in the literature or based on the growth strategy of this species. However, the results may only indicate the relative influence of freshwater on the organisms. Further study is needed to pinpoint the causal factors involved.

TABLE 25. TISSUE BURDEN[a] OF HEAVY METALS IN MUSSELS KEPT IN POTS AT FOUR SITES NEAR THE DENNY WAY REGULATOR OUTFALL, 1978

		Sampling Date		
Station	Parameter	Feb 7	Apr 24	Change
34 m N	Cu	6.5	31.0	+24.5
	Pb	5.2	38.0	+32.8
	Zn	287.5	257.0	-30.5
120 m N	Cu	6.5	21.0	+14.5
	Pb	5.2	34.0	+28.8
	Zn	287.5	205.0	-85.5
380 m N	Cu	6.5	20.0	+13.5
	Pb	5.2	22.0	+16.8
	Zn	287.5	274.0	-13.5
800 m N	Cu	6.5	14.0	+ 7.5
	Pb	5.2	18.0	+12.8
	Zn	287.5	286.0	- 1.5

(a) mg/kg dry weight.

TABLE 26. TISSUE BURDEN[a] OF HEAVY METALS IN OYSTERS KEPT IN POTS AT FOUR SITES NEAR THE DENNY WAY REGULATOR OUTFALL, 1978

		Sampling Date				
		Feb 7		Apr 24		Change In
Station	Parameter	$\overline{X}$	S.E.[b]	$\overline{X}$	S.E.[b]	$\overline{X}$
34 m N	Cu	100.8	31.45	176.7	17.64	+ 75.9
	Pb	2.2	0.65	29.3	2.03	+ 27.1
	Zn	2960.0	705.99	2903.3	619.85	- 56.7
120 m N	Cu	100.8	31.45	240.0	20.82	+139.2
	Pb	2.2	0.65	8.1	1.38	+ 5.9
	Zn	2960.0	705.99	3750.0	241.32	+790.0
380 m N	Cu	100.8	31.45	150.0	47.26	+ 49.2
	Pb	2.2	0.65	6.7	3.18	+ 4.5
	Zn	2960.0	705.99	2906.7	854.91	- 53.3
800 m N	Cu	100.8	31.45	260.0	23.09	+159.2
	Pb	2.2	0.65	6.5	2.13	+ 4.3
	Zn	2960.0	705.99	3710.0	127.67	+750.0

(a) mg/kg dry weight.
(b) Standard error.

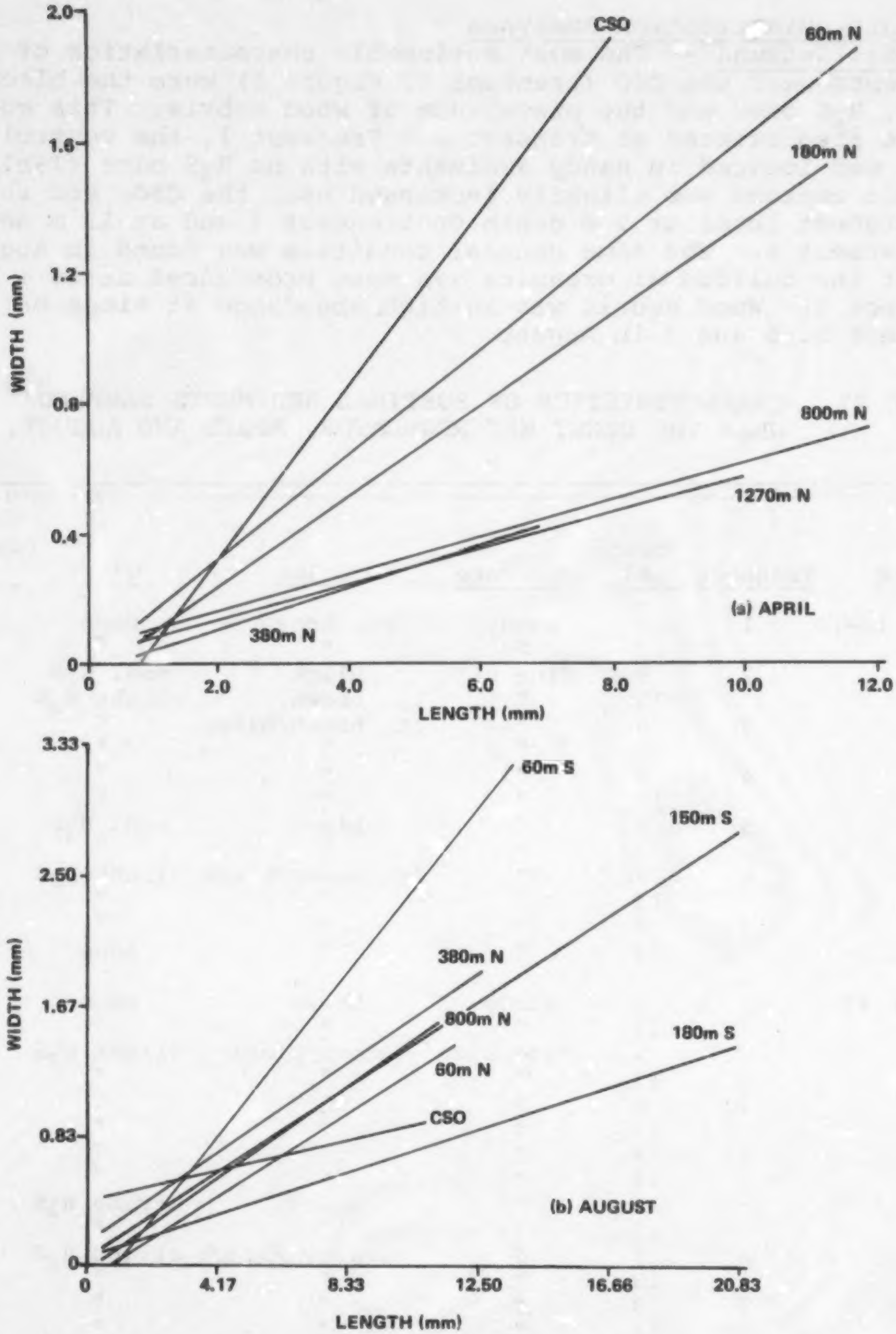


Figure 34. Size data for Enteromorpha collected near the Denny Way Regulator outfall during April and August, 1978.

Community Distribution Analyses -

Subtidal Infauna -- The most noticeable characteristics of the sediments near the CSO (transect 5, Figure 5) were the black color, H_2S odor and the prevalence of wood debris. This condition also existed at transect 2. Transect 1, the control area, was located in sandy sediments with no H_2S odor (Table 27). Organic content was slightly increased near the CSO, and reached its highest level at 9 m depth on transect 4 and at 13 m depth on transect 6. The same general condition was found in August, except the buildup of organics was most pronounced at 13 m on transect 5. Wood debris was in high abundance at sites on transect 5, 6 and 7 in August.

TABLE 27. CHARACTERISTICS OF SUBTIDAL SEDIMENTS SAMPLED(a) NEAR THE DENNY WAY REGULATOR, APRIL AND AUGUST, 1978

Date	Transect	Depth (m)	Texture	Color	Odor	Volatile Organics (%)
April 13-14	1	9	sandy	lt. brown	none	1.52
		13	"	"	"	0.85
	2	9	fine silt	black	mod. H_2S	2.02
		13	"	brown	slight H_2S	2.25
	3	9	"	lt. brown/black	"	2.39
		13	"	"	"	2.26
	4	9	"	"	"	11.73
		13	"	"	"	2.38
	5	9	"	black	mod. H_2S	3.26
		13	"	"	"	3.26
	6	9	"	lt. brown/black	slight H_2S	2.63
		13	"	"	"	7.80
	7	9	"	"	"	2.77
		13	"	"	none	2.24
August 22	1	9	sandy	brown	none	1.11
		13	"	"	"	2.26
	2	9	fine silt	green/black	slight H_2S	2.06
		13	"	"	"	1.84
	3	9	"	"	"	-
		13	"	"	"	2.72
	4	9	"	"	"	1.90
		13	"	"	"	2.60
	5	9	"	black	strong H_2S	2.57
		13	"	"	"	5.54
	6	9	"	lt. brown/black	slight H_2S	2.22
		13	"	"	"	1.39
	7	9	"	"	"	3.18
		13	"	"	"	2.42

(a) Duplicate samples collected at all sites.

The total number of individuals found in the samples from 9 m depth differed appreciably among the sites (Figure 35). The transect 5 samples had the most individuals and this was primary due to the high abundance (1312 organisms) of the pollution-indicating worm Capitella capitata. Infauna was in low abundance at sites on transects 2, 6 and 7. The latter results may be partially explained by the buildup of black sediments at these sites. Transect 2, although located relatively far from the CSO, showed low abundances and this may be due to an eddy of materials at this site, which is immediately seaward of a small cove. The results of Armstrong et al. (1978) coincide with those of the present study with the exception that they found fewer individuals of C. capitata on transect 5.

The results from August were generally similar to those from April. However, very few individuals (12) of C. capitata were found and the species exhibited smaller spacial variability. Furthermore, there was a marked increase in the abundance of the clam Axinopsida serricata in August. This species was found to increase in number with increasing distance from the CSO in April during the present study, and also during the study by Armstrong et al. (1978) a year earlier. These results suggest that the reduced flows from the CSO during summer result in a change in the infaunal composition toward more natural conditions.

The number of individuals found in the samples from 13 m also varied widely among the sites. In April, the fewest individuals were found at the site on transect 5. The number of individuals was also low at sites on transects 1, 2 and 3. The results in August showed that the number of individuals was low on transect 4 and was again low on transect 5. Because the sites on either side of transects 4 and 5 held more individuals, it may be that this parameter is decreased at 13 m by materials from the CSO. These results coincide well with those of Armstrong et al. (1978).

The number of taxa found at both 9 m and 13 m differed among sites, and showed a general decline near the CSO. An exception to this is the 9 m samples taken on transect 5 in April. The higher number of taxa may be related to the larger number of individuals that were collected at that time. The greatest number of taxa were consistantly found in the samples from the control transect (1). These data differed between sampling periods, although the trends were similar. It is difficult to explain the differences between sampling periods. The flux in number of taxa between samplings was most pronounced on transects 5 and 6 at 9 m, and transect 4 at 13 m. It may be that a general northward spread of sewage-related materials at depth results in the effect being most evident on transect 4. Again, these results are in concordance with those of

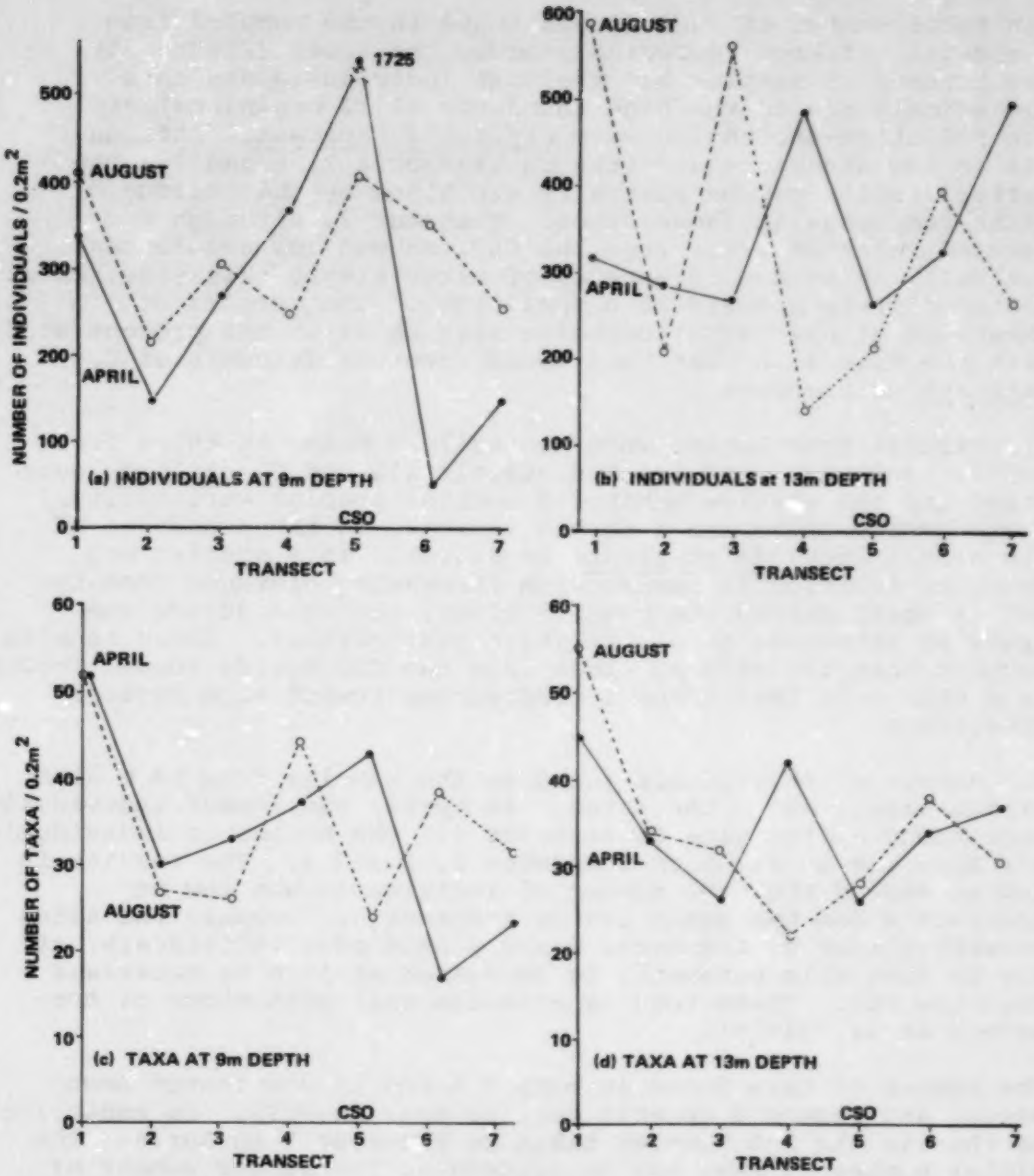


Figure 35. Density of infaunal individuals and taxa found in the subtidal samples collected near the Denny Way Regulator outfall during April and August, 1978.

Armstrong et al. (1978), except that they did not encounter an increased number of taxa at 9 m on transect 5.

Species-richness curves (Hurlbert, 1971) were used to provide an indication of taxocene diversity in the subtidal infauna. Mollusc diversity was lowest at sites on transects 3, 4 and 5 at 9 m, and at the sites on transects 3, 5 and 6 at 13 m in April (Figure 36). The samples from the control transect (1) were most diverse. Diversity was low at sites on transect 5 in August also. Of note is the fact that relatively few mollusc specimens were encountered on transect 5. It appears that mollusc diversity and number of individuals are detrimentally affected by the CSO discharges. The curves for most sites were generally lower in April than in August, which suggests that differences in flow from the CSO may be responsible for the lowered diversity. Mollusc diversity has been shown to be severely affected near sewage outfalls (Green, 1975).

Polychaete diversity also appeared to be affected by the CSO discharge (Figure 37). This effect was evident primarily at the 9 m sites during both April and August. The largest flux between the seasons for this parameter was seen on transect 5 at 9 m and on transect 4 at 13 m. The sites on transect 1 (control) were consistently highest in polychaete species diversity. Infaunal polychaete species diversity followed a very similar trend in the April study by Armstrong et al. (1978). In the present study there was a difference in the distribution of curves between April and August. Polychaete diversity was appreciably lower on transect 5 at 9 m in April and this may be due to changes in flows from the CSO.

A cluster analysis of the subtidal infauna samples from April revealed that sites tended to group by depth, and that the site closest to the CSO (i.e., 9 m, transect 5) was substantially different from the rest of the sites (Figure 38a). The sample on transect 5 at 13 m was also unique among the 13 m samples and clustered with the 9 m samples. The samples were divided into five subgroups (i.e., A-E, Figure 38) and the letters designating these subgroups were plotted on a map of the site locations (Figure 39a). A unique infaunal assemblage existed in April at 9 m on transects 5 and 6. The similarity in infauna at sites 9/2, 9/3 and 13/5 may have been related to the similar substrata at those sites. Black sediment was found at each location (Table 27). The sediments at the other sites at 13 m were light brown in color.

An eddying of materials immediately seaward of the cove adjacent to transects 2 and 3 may be responsible for the disposition of organic particulate matter at 9/2 and 9/3. The results of the cluster analysis by Armstrong et al. (1978) were similar to the results obtained in this study. However, in their study, the site at 9 m on transect 2 clustered with the site on

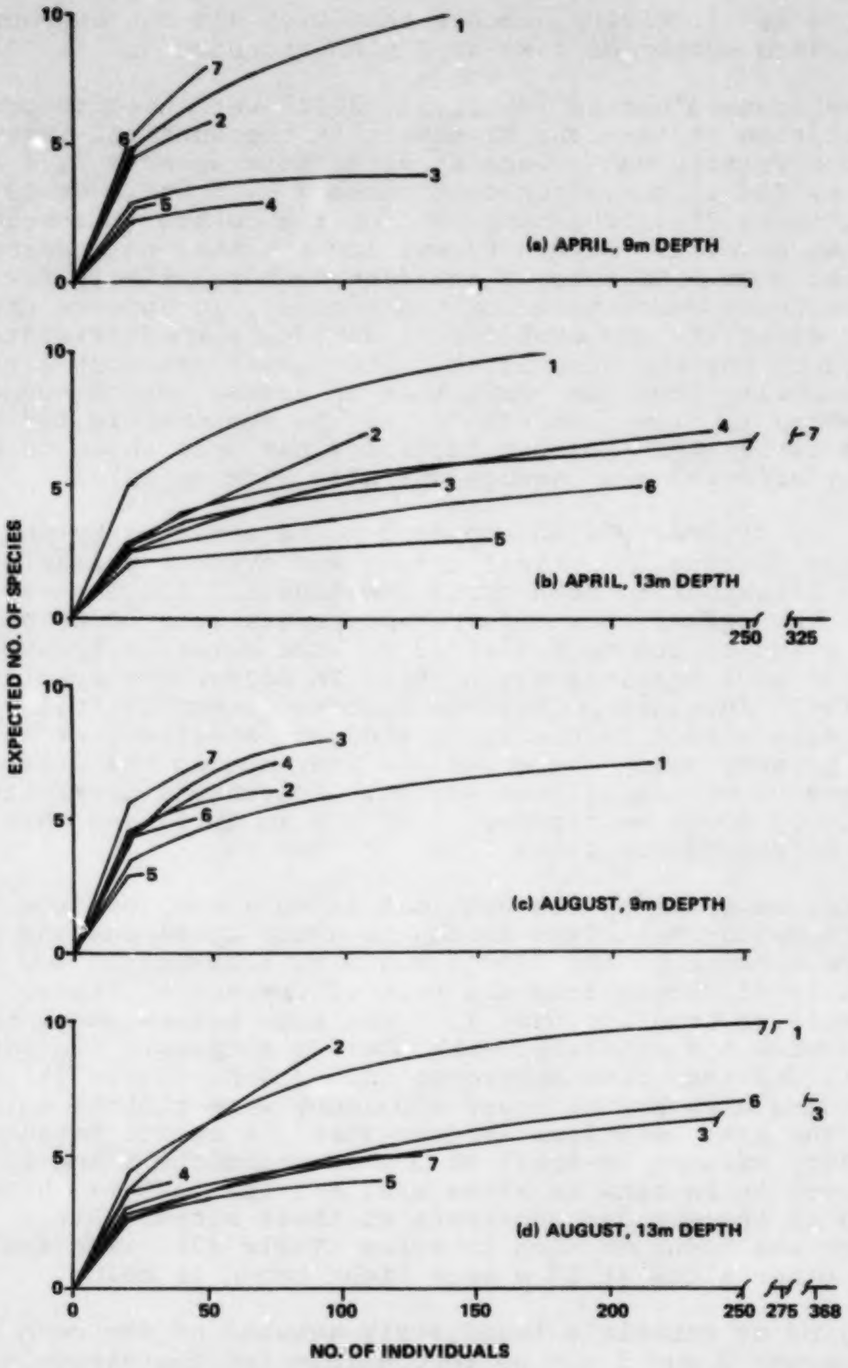


Figure 36. Species-richness curves for molluscs collected near the Denny Way Regulator outfall during April and August, 1978. The numbers indicate sampling transects.

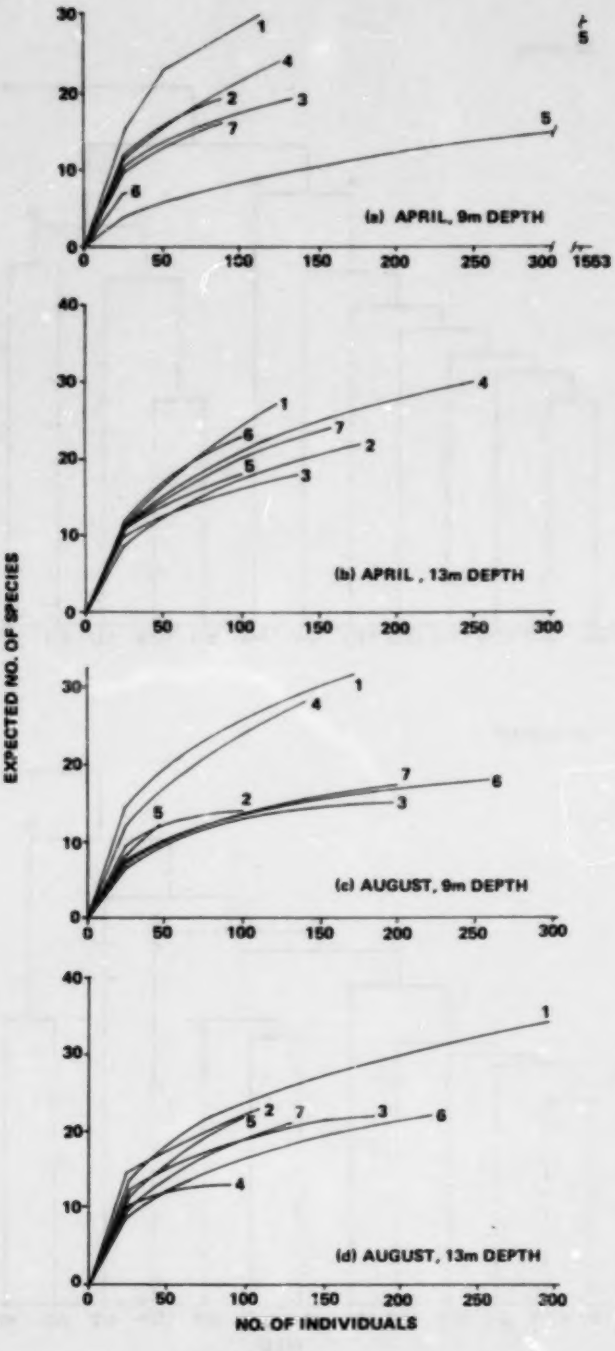


Figure 37. Species-richness curves for polychaetes collected near the Denny Way Regulator outfall during April and August, 1978. The numbers indicate sampling transects.

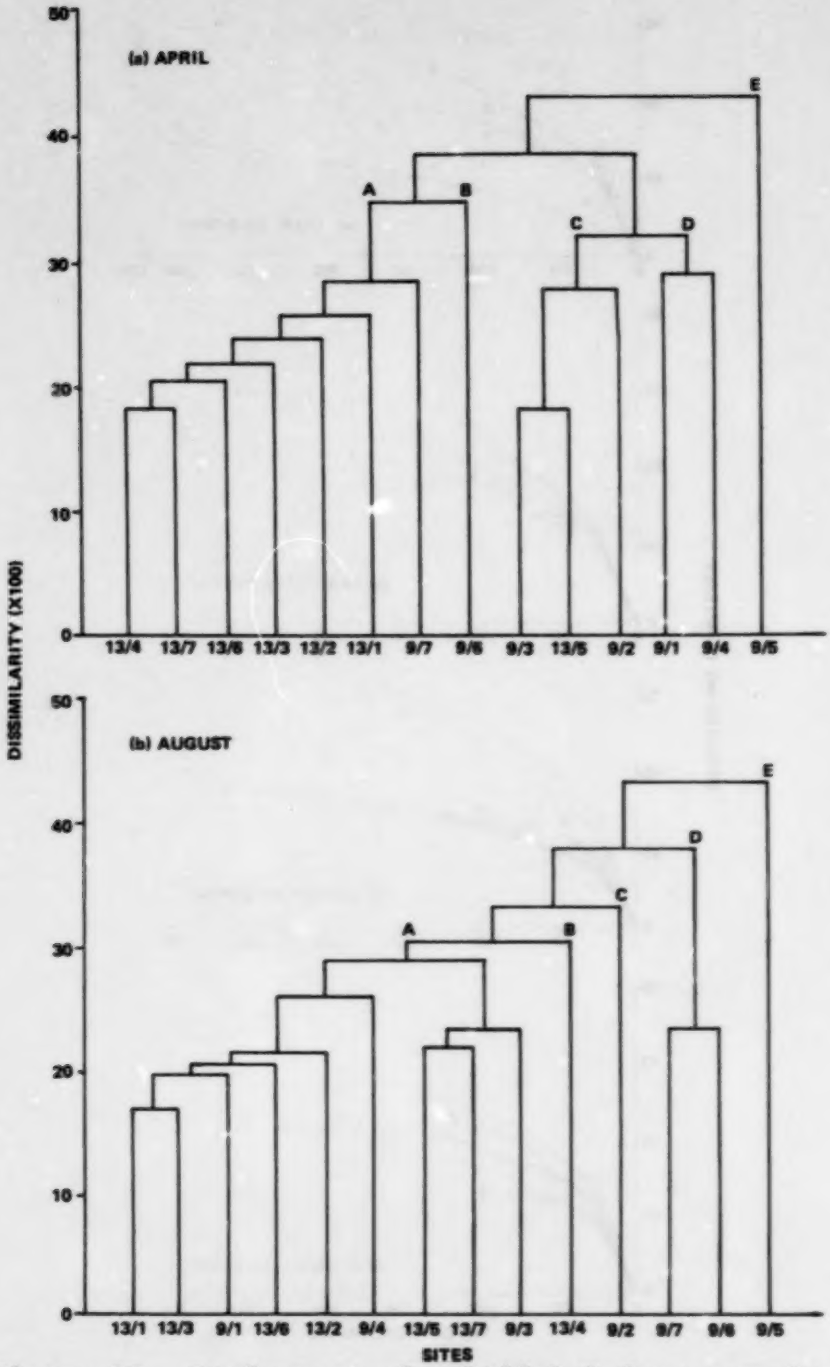


Figure 38. Dendrogram of subtidal infauna samples collected near the Denny Way Regulator outfall during April and August, 1978. The site designations are given as depth (m)/transect.

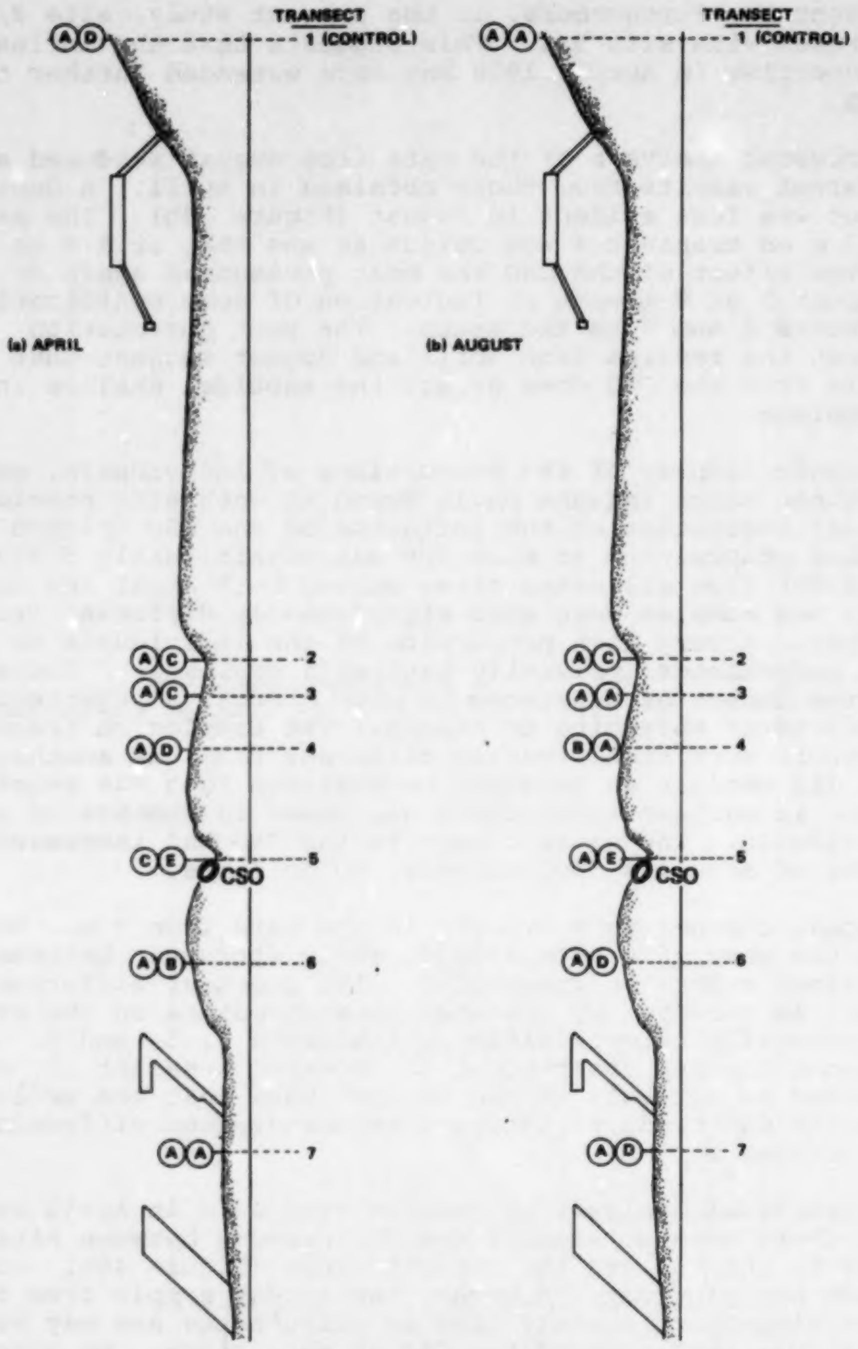

TRANSECT
A D
1 (CONTROL)
(a) APRIL
A C
2
A C
3
A D
4
C E
5
CSO
A B
6
A A
7
TRANSECT
A A
1 (CONTROL)
(b) AUGUST
A C
2
A A
3
B A
4
A E
5
CSO
A D
6
A D
7

Figure 39. Positions of subgroups of sites from cluster analysis of samples of subtidal infauna collected near the Denny Way Regulator outfall during April and August, 1978.

transect 1. Furthermore, in the present study, site 9/1 clustered with site 9/4. This suggests that the influence of the overflow in April, 1978 may have extended further to the north.

The cluster analysis of the data from August produced strikingly different results from those obtained in April. A depth effect was less evident in August (Figure 39b). The assemblage at 13 m on transect 4 was unique as was that at 9 m on transect 2. The effect of the CSO was most pronounced again at transect 5 at 9 m with an indication of some modification on transects 6 and 7 to the south. The poor correlation between the results from April and August suggest that flow levels from the CSO does affect the subtidal shallow infaunal assemblage.

A graphic display of the proportions of individuals, among the three major infauna phyla found at each site provides a partial indication of the influence of the CSO (Figure 40). Infauna composition at site 9/5 was significantly different ($p < 0.05$) from all other sites during both April and August. These two samples were also significantly different from one another. A very high proportion of the individuals in April were polychaetes (primarily Capitella capitata). Conversely, a large number of crustecea (primarily Nebalia pugettensis) was found at this site in August. The samples on transect 1 (control) were significantly different from one another, but they did exhibit an infaunal composition that was relatively higher in mollusc individuals and lower in numbers of polychaete individuals. The sites closer to the CSO had increased ratios of annelids (polychaetes) to molluscs.

Seasonal changes were evident in the data from 9 m. Samples from the same site were significantly different between samplings except at transect 2. The greatest difference (i.e., as measured by distance between points on the graph) was generally between sites on transects 4, 5, and 6. If seasonal changes observed at the control transect (1) can be regarded as natural, it can be concluded that the effluent from the CSO tends to increase between-season differences in the infauna at 9 m.

The graphical analysis of samples from 13 m in April revealed that there were no significant differences between sites close to the CSO and the control sites (Figure 40b, confidence limits not plotted). However, the August sample from transect 4 was disproportionately high in polychaetes and may suggest a possible influence of the CSO at this depth. No significant differences between seasons were evident at any 13 m site other than that on transect 4.

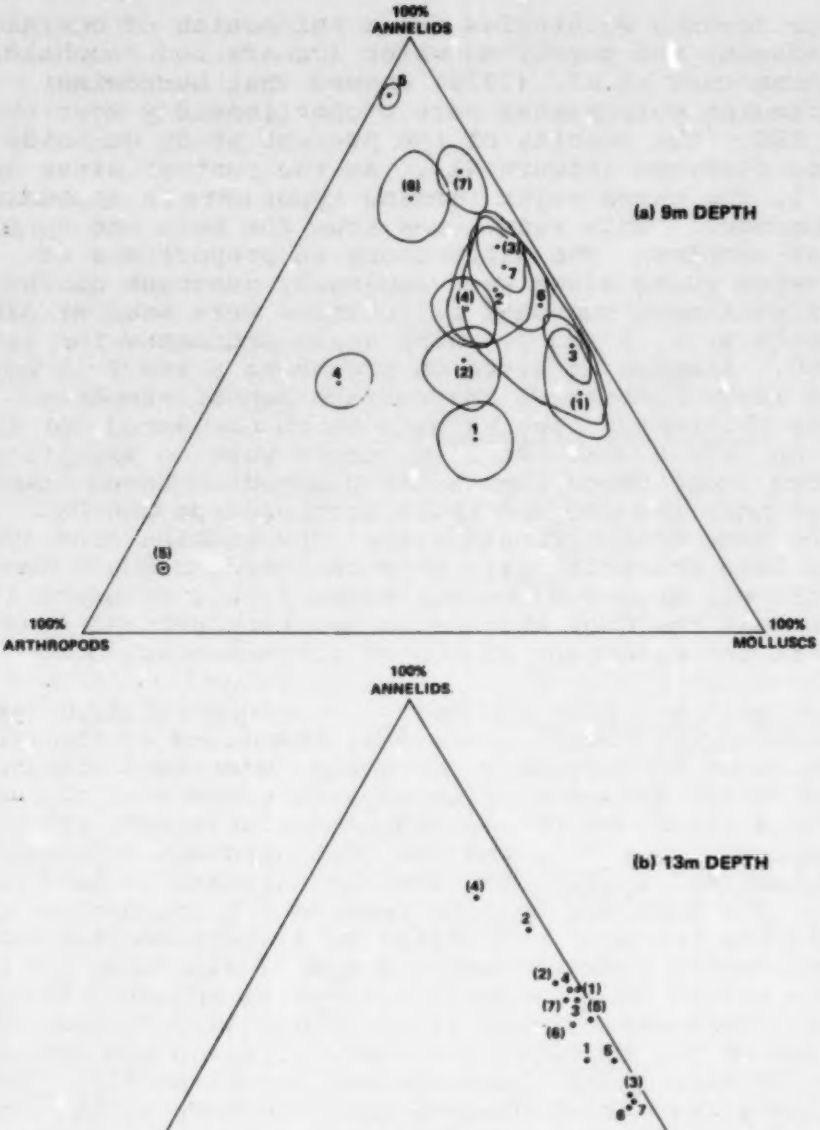


Figure 40. Proportions of the total numbers of annelids, arthropods and molluscs collected near the Denny Way Regulator outfall during April and August, 1978. The numbers designate transects; those in parentheses are for August. The circles indicate 95% confidence intervals.

Polychaete feeding strategies are a reflection of characteristics of the sediment and overlying water (Jumars and Fauchald, 1976). Armstrong et al. (1978) showed that burrowing, deposit-feeding polychaetes were proportionately most abundant near the CSO. The results of the present study coincide with those findings (Figure 41). At the control sites on transect 1, the three major feeding types were in approximately equal abundance. This result was true for both the April and August samples. The differences in proportions of feeding types among sites were generally greatest during April. Significant seasonal differences were seen at sites on transects 4, 5, 6 and 7, which again indicates the influence of the CSO. Samples at sites on transects 6 and 7 in August contained large numbers of the surface deposit-feeding polychaete Prionospio steenstrupi, which accounted for their position on Figure 41a. At 13 m, there were no significant differences (confidence limits not plotted) between samples from sites near the CSO and those further from the CSO within the same month (Figure 41b). The samples from April tended to have proportionally more burrowing deposit feeders. This result was true for control sites (i.e., transect 1) and sites near the CSO, which suggests that natural seasonal changes are the prominant source of variation at 13 m.

Intertidal Soft-Sediment Community -- A zone of black sediment with a distinct H_2S odor exists near the mouth of the CSO. This zone appears to be intensely scoured by overflows and this is reflected in the relatively low organic content of the sediments and the high abundance of oligochaetes (Table 28). The polychaete Capitella capitata was the most abundant infaunal species in the intertidal zone. Its abundance appears to have been related to the CSO, and this is best seen by comparing sites e, f and g in the CSO cove with sites h, i and j located at the same tidal height near transects 2 and 3 (Figure 5). This difference was evident in April but not in August. Site C located in the wash-out zone still held a large number of individuals of C. capitata in August, although the overall abundance of this species was reduced significantly. Intense desiccation stress and decreased overflows may be the reason for the reduced abundance in August.

Periphyton -- Data on periphyton communities are available for April only. Blocks set out in July were covered with a dense mat of the green bladed alga Enteromorpha linza in August, thus excluding any microalgal assemblage development.

There was no clear evidence of a reduction in periphyton diversity except on the block closest to the CSO (Figure 42). These results differ from those of Armstrong et al. (1978) who did see an indication of declined diversity further from the CSO.

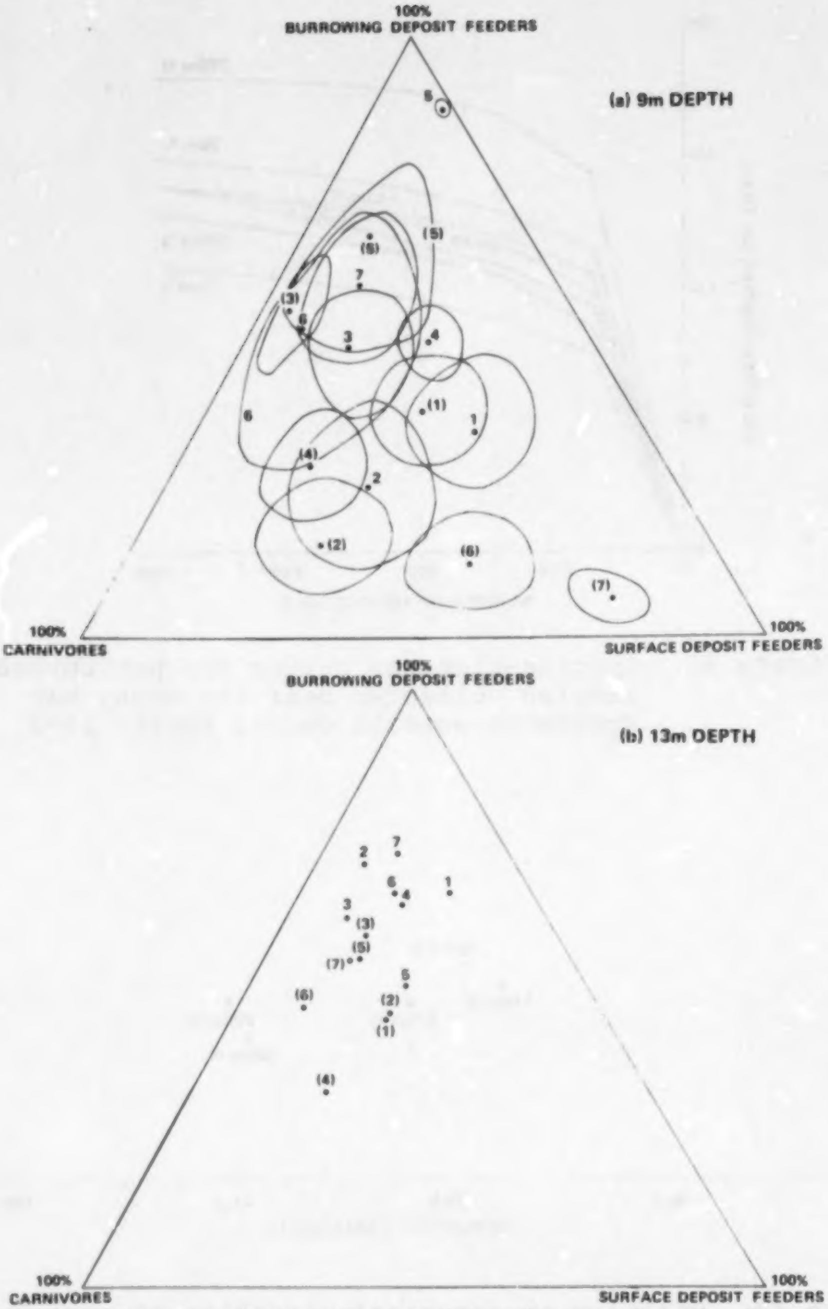


Figure 41. Proportions of total numbers of polychaetes within each of three feeding-type categories, for samples collected near the Denny Way Regulator outfall during April and August, 1978. The numbers designate transects; those in parentheses are for August. The circles indicate 95% confidence intervals.

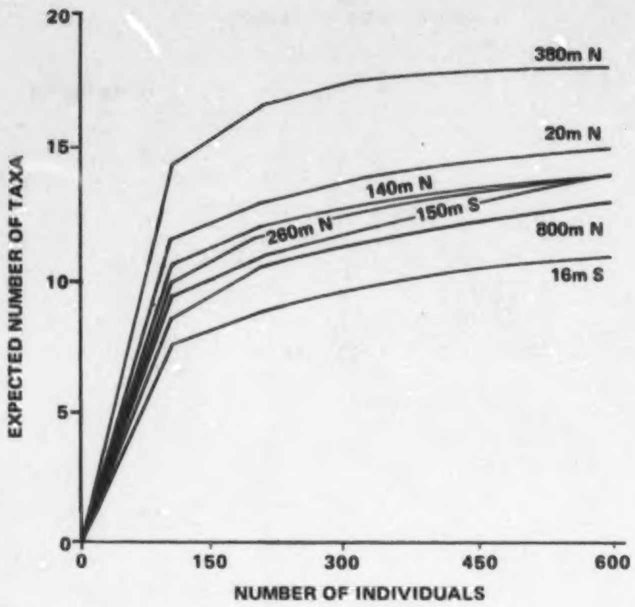


Figure 42. Species-richness curves for periphyton samples collected near the Denny Way Regulator outfall during April 1978.

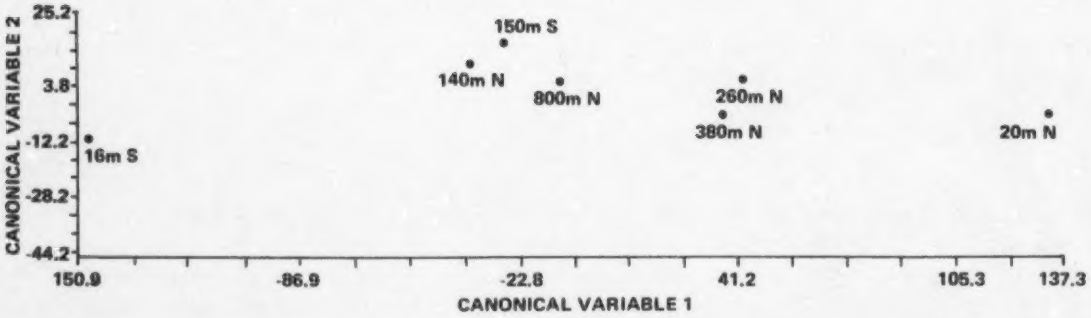


Figure 43. Position on canonical variables of periphyton samples collected near the Denny Way Regulator outfall during April 1978.

TABLE 28. CHARACTERISTICS AND ANNELID(a) DENSITIES OF INTERTIDAL SOFT SEDIMENTS SAMPLED NEAR THE DENNY WAY REGULATOR, APRIL AND AUGUST, 1978

Date	Site	Texture	Color	Odor	Volatile Organics (%)	Annelid Abundance (No. Individuals)
April 24	a	silty-sand	black	H_2S	0.86	42
	b	sparse cobble	brown	"	0.83	51
	c	silty-sand	black	"	7.80	121
	d	sparse cobble	brown	"	0.99	122
	e	"	"	"	1.35	41
	f	cobble-sand	"	"	1.03	53
	g	sm cobble, clay	"	"	0.87	242
	h	sm-med cobble, sand	"	none	0.66	3
	i	"	"	"	0.64	0
	j	"	"	"	0.70	1
Aug. 17	a	silty-sand	black	H_2S	1.49	6
	b	"	"	"	0.71	8
	c	"	"	"	2.32	70
	d	"	"	"	0.72	9
	e	"	"	"	1.51	10
	f	"	"	"	1.02	9
	g	"	"	"	0.59	43
	h	"	"	"	0.73	42
	i	"	"	"	0.52	14
	j	"	"	"	0.68	23

(a) *Capitella capitata*. All counts are totals for four 31.3 mm diameter cores.

A plot of samples along canonical variables 1 and 2 did, however, indicate that the periphyton communities at the two sites nearest the CSO differed from the rest of the samples (Figure 43). Of the taxa that entered the discriminant function, *Gomphonema* was in high abundance and *Synedra* was in low abundance, at the 16 m S site. *Amphora* was also in relatively high abundance at this site. The 20 m N site had a very high abundance of the filamentous diatom *Melosira nummuloides*. The results of this analysis coincide with the conclusions of Archibald (1972) who found that diatom diversity did not always follow a pollution gradient, and that autecology of dominant species proved to be the most important criterion for assessing water quality.

Boulder Wall Taxa -- The majority of cover at +0 m (MLLW) along the rocky portions of the study area was comprised of macroalgae. The sites 30 m north and south of the CSO were primarily cobble in sand. The remainder of the sites were the stable boulders forming the wall.

Species-richness curves for macroalgae at in April were lowest at the sites located 150 m south and 120 m north of the CSO (Figure 44). The sites closest to the CSO held more species than the former two sites but less than the remaining sites further from the CSO. Recent ecological work concerning disturbance versus species diversity may provide a partial explanation for this condition. It has been shown that disturbance of rocky intertidal areas may raise species diversity by opening primary space for colonization by fast growing and reproducing (r-selected) organisms (Paine, 1966; Dayton, 1971; Menge, 1976; Osman, 1977). High flows from the CSO in the period prior to the April survey may be regarded as a disturbance. The species inhabiting the low intertidal zone, especially during spring, are primarily ephemerals (r-selected). Therefore, relatively high disturbance of cobble sites near the CSO may have caused the increased diversity there. The lowered diversity at the stable boulder wall sites at 120 m north and 150 m south of the CSO may indicate the effect of sewage-related, water-borne materials other than

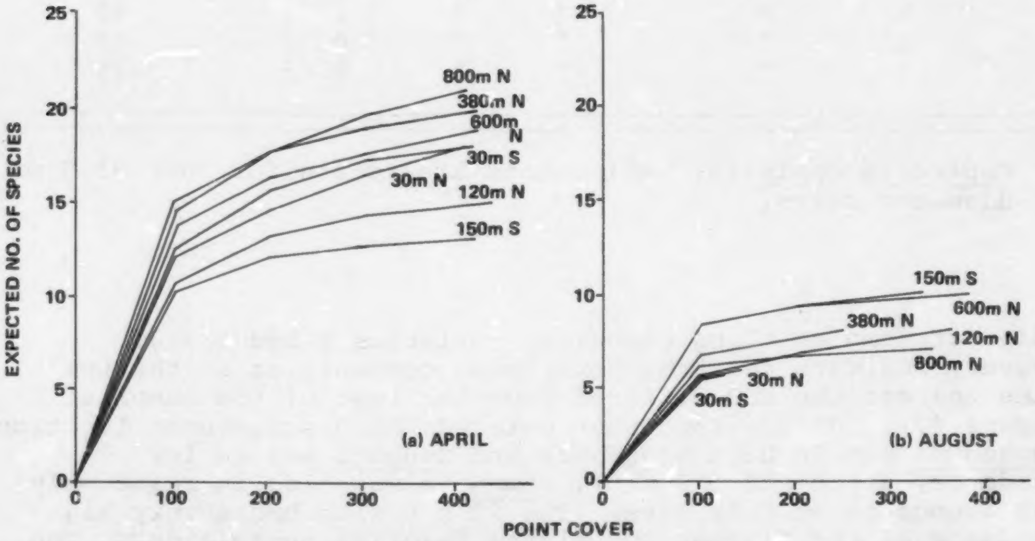


Figure 44. Species-richness curves for macroalgae collected near the Denny Way Regulator outfall during April and August, 1978.

scouring sediments. Results presented elsewhere in this report indicate that turbidity, measured as percent light transmittance, is moderately high within approximately 300 m of the CSO. Zimmerman and Livingston (1976) concluded that increased turbidity (by Kraft Pulp Mill effluent) was the most important factor in modifying macrophyte community structure at their study sites in Florida.

A plot of the boulder wall sites along canonical variables one and two revealed that the effect of the CSO may extend to the site 380 m north (Figure 45). This site was more similar

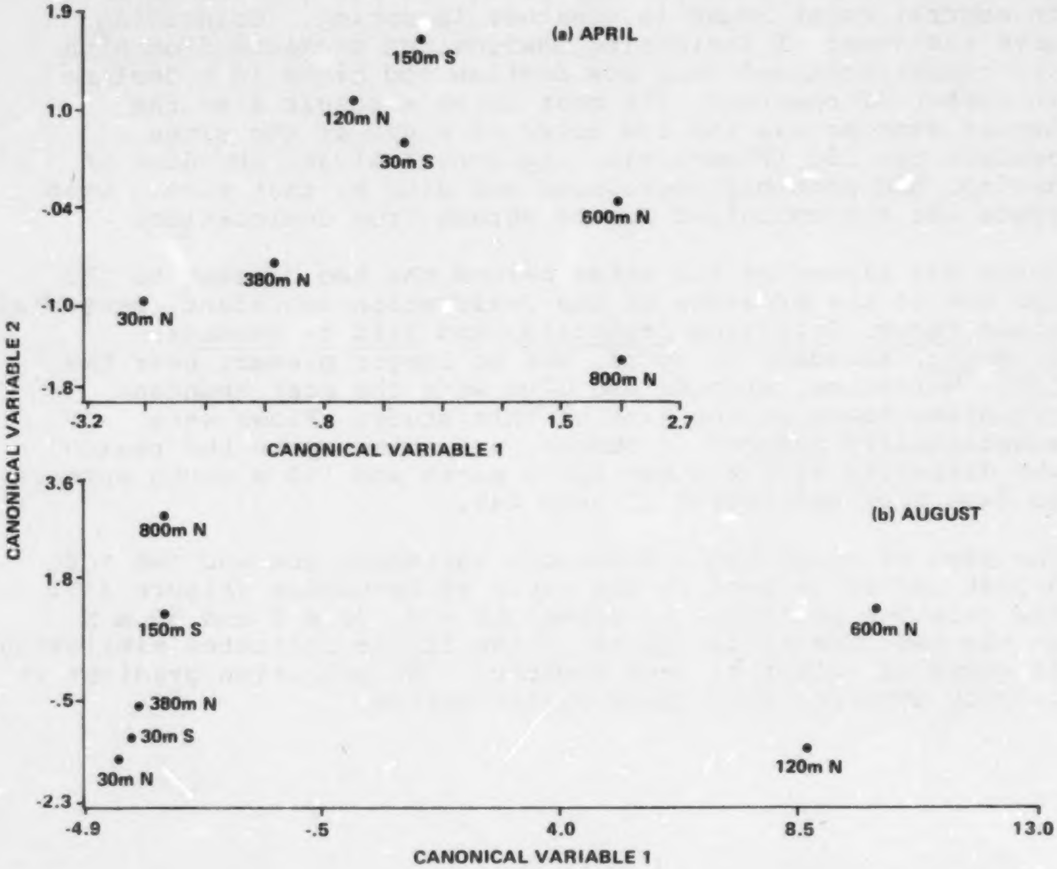


Figure 45. Position on canonical variables of samples of boulder wall taxa collected near the Denny Way Regulator outfall, 1978.

to the sites closer to the CSO than it was to the sites further away. All taxa encountered entered into the discriminant function, with differences in the cover of barnacles being the most significant. As reported by Armstrong et al. (1978), the abundance of *Fucus* increased, and the abundance of *Sargasam* decreased, with increasing distance from the CSO. The cover of the filamentous red alga *Polysiphonia sp.* appeared to decrease nearer the CSO. Another delicate red alga, *Delesseria decipiens* appeared to increase in abundance nearer the CSO.

The data on low littoral communities from August differed considerably from those collected in April. Fewer species were found and the cover was generally less in August. Thom (1978) has shown that the number of species of benthic algae in central Puget Sound is greatest in spring. Coinciding with the onset of increasing desiccation pressure from high air temperature and very low daytime low tides is a decline in number of species. The most notable result from the August samples was the low cover of algae at the sites nearest the CSO (Figure 44). Ephemeral algae, abundant in spring, had probably reproduced and died by that time. Open space was not colonized due to stress from desiccation.

Cover was higher at the sites beyond the two closest to the CSO due to the presence of the desiccation-resistant, perennial algae *Fucus*, *Gigartina papillata*, and *Iridaea cordata*. *S. Mutic*, abundant in April, was no longer present near the CSO. Barnacles, diatoms and *Ulva* were the most abundant organisms there at the time of this study. Flows were substantially reduced in summer, and this may be the reason why diversity at the sites 120 m north and 150 m south appears to have been unaffected (Figure 44).

The plot of sites along canonical variables one and two for August may be related to the cover of barnacles (Figure 45). The relative positions of sites 380 m N, 30 m S and 30 m N in the two-dimensional space of the figure indicates similarity in terms of extent of rock coverage. No pollution gradient is readily apparent from these relationships.

SECTION 6

DISCUSSION

EFFECTS OF DISCHARGES ON LITTORAL FOOD CHAINS

Freshwater Environment

The original intent of the freshwater biota studies was to describe the numerical abundance, biomass, and types of benthic organisms in control areas and areas receiving sewer discharges in Lake Washington. The discussion would be incomplete, however, without relating these findings to the possible effects on fish at those sites.

It should be realized by the planner and fishery manager that in a system as large and diverse as Lake Washington it would be an impossibility to thoroughly assess the specific effects on fish resulting from changes in the benthic community. A specific effect on one species of fish may indirectly affect several other species throughout the food chain. The possible impacts to the system are virtually limitless. The purpose of the following discussion is to consider the present findings for the benthic communities relative to possible effects on the feeding opportunities of fish in those areas.

Indigenous Fish Species and Principal Food Types -- A total of 39 species of fish are known to occur in the Lake Washington drainage. These include a number of sportfish (pink salmon, chum salmon, coho salmon, sockeye salmon and kokanee, chinook salmon, coastal cutthroat trout, rainbow trout and steelhead, brook trout, Dolly Varden, lake trout, smallmouth bass, largemouth bass and black crappie) as well as important fish-prey species (such as speckled dace, redside shiner, threespine stickleback and six species of sculpins, with the prickly sculpin being the most abundant in Lake Washington) (Wydoski, 1972). Of the species common to Lake Washington proper, at least 14 have been found to depend on benthic organisms for all or part of their food, including largemouth bass (Stein, 1970), cutthroat and rainbow trout (McAfee, 1966; Wydoski and Whitney, 1979), black crappie (Wydoski and Whitney, 1979), smallmouth bass (Emig, 1966), and a prominent prey species, the prickly sculpin (Rickard, 1979).

Although sockeye salmon are an economically important species in Lake Washington, they may not be as dependent on the benthos as other species. Woodey (1972) found that sockeye fry live and grow in the pelagic zone of the lake for one or two years before migrating to sea. These young fish feed primarily on planktonic animals.

The food habits of coho and chinook salmon juveniles in Lake Washington are likely similar to those of the other salmonids, which depend directly or indirectly on the benthic communities. It is not certain, however, what proportions of coho and chinook are reared in hatcheries and reared naturally in the lake.

One of the most abundant fish in Lake Washington, and an important food item for larger fish is the prickly sculpin, or cottid. This species may depend more on benthic food items than any other fish in the lake (Rickard, 1979). Since the cottid provides a valuable food base for larger predatory species, any change in the abundance of its benthic food organisms could have an impact on the entire food chain.

Discharge Impacts on Feeding Opportunities for Fish -- It is obvious from these studies that many species of fish depend on benthic food sources in Lake Washington. The following is a discussion summarizing our findings concerning the benthic communities at our study sites and a description of the possible effects on the feeding opportunities of the fish in those areas.

At Control Sites 3 and 4 there were generally moderate to strong negative correlations between the numbers and biomass of organisms and depth, whether considering types of organisms separately or combined. This means that there were generally higher numbers of organisms in shallow water. The only exception was the Pisidium spp. or freshwater mussel which either showed no relationship with depth or was found in slightly higher numbers in deep water. These data would indicate that at control sites the possibility for benthic feeders to encounter food items would be greater in shallow water, and equal at constant depth. This was not always the case at the SD and CSO sites.

At CSO 023 there were generally higher predicted total numbers of organisms (predominantly oligochaetes) and greater biomass near the outfall. If fish feed in this area, it would mean a greater opportunity to encounter food items near the source of the discharge. For fish selecting a single type of organism, however, this would not always be true at CSO 023. Chironomids were generally found in low numbers near the outfall but at a larger average size. This means that fish selecting only chironomids would encounter them less frequently near the outfall but may receive a "normal" food volume due to the larger average size of the prey items. Unlike chironomids, the predicted number and biomass of oligochaetes in February was greater near the source of the discharges. In September there were no relationships between numbers and biomass of oligochaetes and distance from the outfall.

This suggests that if fish feed near the outfall in February, they would encounter more food items. In September, however, fish that feed throughout the area would encounter the same number of oligochaetes regardless of the location. It is possible that between February and September higher feeding activity, rather than pollution effects on food availability, was responsible for the reduced relative numbers and biomass of oligochaetes near the outfall. Since copepods and mussels were always found in fewer numbers near the outfall, it seems likely that the discharge is a contributing factor. Nematodes, on the other hand, were always found in higher numbers near the outfall at CSO 023. This indicates that either fish do not feed on nematodes near the outfall or that the discharge increases the number of nematodes near the outfall and therefore, the opportunity to encounter food items. This raises the possibility that the distributions of some benthic species around an outfall may reflect indirect, rather than direct, effects of the discharges, i.e., that distributions of the benthic biota are dictated by the feeding patterns of fish, which are in turn influenced by the discharges.

Qualitative relationships between the discharges and feeding opportunities for fish are obviously quite speculative for CSO 023, as well as for any of the other three outfalls studied, but generally follow an application of the above logic to the relationships depicted by Figure 27. In a few cases, such as for CSO 023 in both February and September, the numbers and/or biomass of the benthic biota were dominated by a single type of organism; this effectively removes one variable in the complex cause-effect relationships. Subsequent speculation would then focus on the compilation of a list of fish predator species for that type of organism, and the relative depth/temperature preferences and toxicity tolerances for each (if available).

Toxicity responses are particularly important in those instances when the predator may be attracted to the outfall by enhancement of the numbers and/or biomass of the prey organisms, such as observed for oligochaetes in February, or nematodes in September at CSO 023. The impacts of ingested toxicants on the health of the predator fish and the toxic and smothering effects of the discharges entering breeding areas are additional important - and complex - topics needing further consideration.

Quantitation of Discharge Impacts on Benthos and Fish -- The quantitative aspects of the question of discharge impacts are only slightly less difficult to assess than the behavioral problems, but a useful attempt can be made to estimate order-of-magnitude potential effects on the ultimate biomass of non-specific predator fish. This calculation is based on the relationships given in Figure 27, for depth-independent functions of numbers and biomass of taxonomic groups as functions of distance from an outfall. From the plotted relationships, one may estimate the biomass depletion or enhancement of each type of organism around the outfall. The sum of these values, taking into consideration the probable annual numbers of generations, may in turn be converted to an estimate of fish biomass lost or gained due to discharge impacts.

CSO 023 will be used here for purposes of illustration because it has minimal depth variation within the impacted zone, and had a significant relationship between total weight of organisms and distance from the outfall. Also, as opposed to those of the storm drains, the impacted area of CSO 023 was well covered by the biological sampling array. The size of the impacted area was first determined from a comparison with mean total biomass data from the two control sites. For February, a circle with a radius of 42 m was used to represent the area of elevated total biomass/core around the CSO 023 outfall. The biomass/core relationships in Figure 27 were converted to biomass/m^2 by multiplying by 1514 cores/m^2 (calculated for a core diameter of 29 mm). The area of impact was then reduced to a series of concentric circles, each 1 m in width, and the total area of each was multiplied by the relative biomass enrichment value. The sum of these products was then converted from total dry weight to total wet weight of benthic biota by dividing by .14, the fractional weight of dry matter in live oligochaetes (Elliott, 1971). Then, assuming an average of one generation/year for these prey organisms, and a prey-predator tissue conversion efficiency of 10%, an estimate of potential gain of fish biomass due to sediment enrichment by CSO 023 was obtained. This value was 4.7 kg total fresh wt. of fish per year, based on an increase of 47.3 kg of prey biomass. The total mean baseline prey biomass for a comparable area and depth at the control sites was determined to be 57.9 kg fresh weight, indicating that the enrichment of 47.3 kg/yr estimated for biomass of prey organisms around the CSO 023 outfall represents an increase of 82% over baseline levels. Using the same methodology, oligochaetes alone were found to account for 43.1 kg, a 74% increase over the baseline total for all organisms sampled. These calculations for trophic level conversion assume that the fish are 100% successful in locating and consuming all of the prey organisms, and in this sense the estimates are obviously too high.

The preceding calculation represents a very simplified approach to an exceedingly complex question, and should not be interpreted or expressed as a close estimate. Its principal value is to provide an order-of-magnitude estimate for one example of discharge impact on fish in Lake Washington. Further, if used as an extreme for those weight/distance relationships shown in Figure 27, together with knowledge of the dimensions of impacted areas, it can be used to estimate the magnitude of potential impacts for other taxa and stations. For example, at CSO 044 in September the data indicated a depletion of chironomid biomass around the outfall, but the sub-background weights were limited to a circle with an 8 m radius. This impacted area was appreciably smaller than that determined for oligochaetes at CSO 023, as was the change in biomass per unit distance. A comparison of these two relationships, as depicted by Figure 27, indicates that the net decrease in prey and potential predator (fish) biomass at CSO 044 was perhaps 1% of the increase calculated for oligochaetes at CSO 023. This would mean a loss on the order of 0.5 kg fresh wt. of chironomids, and .05 kg fresh wt. of fish.

Marine Environment

The coastland of Elliott Bay constitutes a substantial fraction of Seattle's total marine shoreline (Figure 1). The present study investigated an estimated 17% of this feature, approximately 15% of which was found to be impacted by discharges from the Denny Way Regulator CSO. Of the shallow (0-13 m depth) nearshore area, including both hard and soft substrata, about 8% was found to be biologically altered by the CSO discharges.

Much of the nearshore region in Elliott Bay is dominated by man-made structures such as piers and sea walls. Since the study area for the present project is relatively devoid of such structures, it may represent the most natural habitat available to the bay's biological communities, including salmonid species. From this perspective, semi-natural biological assemblages in the bay constitute a diminished resource and the additional physiological stresses contributed by polluted discharges represent a serious threat to their survival and well-being.

The benthic food web in Elliott Bay is detrital-based, and depends upon input of carbon from phytoplankton, benthic algae and allochthonous material. The results of the present analyses indicate that the primary productivity of benthic macrophytes (in terms of standing stock measurements) is significantly altered near the Denny Way CSO. Because the boulder wall near the CSO is an important habitat for macrophyte production and is not prevalent elsewhere in the bay, the observed alteration may represent a significant impact on the total productivity of the bay's detrital-based benthos.

The dispersion of particulate toxicants, and the alteration of substrate consistancy by a large marine CSO such as that at the Denny Way Regulator may also more directly affect the feeding success of fish*. In general, the rocky and gravelly-sand habitats in the Seattle area support a larger number of fish species than do silt-mud habitats. Salmon, herring, anchovies, rockfish, surf perches, greenlings, gunnels, sand lances, cottids, pipefish and wolffish occur in rocky-gravel habitats. In contrast, sculpins and lampreys prefer areas of silt and mud. Smelt, flounders and stickleback are found on both types of substrate (B.S. Miller, University of Washington, personal communication). Near the Denny Way CSO, the intertidal substrate is rocky, whereas that of the contiguous subtidal region is silt-mud. Physico-chemical disturbances by the CSO in the form of increased turbidity and siltation, and of increased concentrations of particulate toxicants, may result in corresponding changes in the faunal composition and abundances of the benthic fauna. These changes in turn can influence the feeding success of fish such as salmonids, which selectively ingest the small epifaunal crustaceans that inhabit rocky-gravel substrates (J.Q. Word, University of Washington, personal communication). The alteration of a benthic substrate by fine particulates from CSOs and SDs would tend to favor fish species such as the Dover sole, a non-selective consumer that does well in a variety of habitats.

There are indications that shifts in the benthic assemblages near the Denny Way CSO may be seasonal as was indicated for the communities studied in Lake Washington. In the spring, toward the end of the wet season, which is characterized by numerous overflows, a deposit feeding infaunal community predominates near the outfall. However, the dominant summer (dry) season organism is a small epifaunal crustacean, Nebalia sp.. It is anticipated that this shift in type of prey organisms may result in a concurrent shift in the predominant fish species.

Due to the comparatively natural configuration and substrate composition of the surrounding shoreline, and to the ecological importance of this semi-natural habitat, the Denny Way CSO probably presents the greatest threat to the Elliott Bay biota; however, the salmonids and other fish and their supportive food webs are also threatened by other inputs. Due in part to the influence of more than 20 other CSOs and unknown numbers of storm drains, the water quality of the bay has for years been characterized as fair to moderate. The levels of coliform bacteria are typically higher within the bay than outside it (Metro data), and significantly elevated levels of metals and PCBs have been found in the sediments of the highly industrialized Duwamish River estuary (Tomlinson et al., 1976). It is in view of this more widespread deterioration of the bay's natural environment that evaluation and abatement of discharge impacts on naturally productive areas seems immediately imperative.

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*Fish occur in considerable numbers in the bay, and there is a significant annual salmonid run in the in-flowing Duwamish River. Juvenile salmonids, either from natural or hatchery stocks, migrate downstream in spring and summer months through the Duwamish estuary and Elliott Bay. These fish spend much of their time in nearshore habitats in these areas.

EXTRAPOLATION OF PRESENT FINDINGS TO OTHER OUTFALL SITES

The results obtained in the present study may prove useful as support information for management decisions concerning CSO and SD construction or modifications. However, the extrapolation of this information to other CSO or SD systems should be approached with caution. The facilities investigated herein are representative of residential drainage basins having a moderate to high number of overflows during a typical weather year of about 100 cm of rainfall. CSO 023 and SD 7 may have atypical discharge levels of chlorinated hydrocarbons for residential areas; this possibility should be investigated, bearing in mind that the fraction of the observed biological impacts directly attributable to these toxicants is unknown.

CSO and SD effluent from commercial and industrial areas (using the results presented above for Denny Way studies as an example) might be expected to have higher levels of heavy metals and organic toxicants, and lower concentrations of viruses and chlorinated hydrocarbons - the relative impacts of these comparisons are undefined except for the higher disease potential at the residential CSO site. Generally speaking, storm drainage is likely to be lower in total particulates and particulate phosphorus than is CSO effluent. As opposed to that found in storm drainage, the organic matter discharged by CSOs contains a large fraction of materials processed by human digestion, and may therefore be more immediately available as an energy source to support and enrich the biological communities of the receiving waters or sediments.

One final note of caution is that the biological impacts attributable to any outfall are functions not only of concentration and species of discharged pollutants, but also of their total mass loading to a given area. Greater loading may result in either a greater area or a greater intensity of influence, or both. The area of impact is also dependent on receiving water circulation. The relative effects of loading magnitude and nearshore circulation on the local biota were not quantified by the present analyses.

EXTENT OF NEARSHORE WATERS AFFECTED BY DISCHARGE PARTICULATES

Freshwater Environment

Based on the findings of the present study, a number of general, and perhaps useful, observations can be made regarding the extent of influence of CSO and SD particulates discharged into Seattle's nearshore waters. If the CSOs and SDs studied in Lake Washington may be considered typical in terms of the physical (if not the chemical) aspects of their discharges, the following perceptions evolve.

Whereas discharge plumes may cover contiguous areas of up to ten hectares (25 acres), depending on characteristics of local circulation, the typical outfall/discharge combination produces detectable plumes covering five hectares or less, and persisting for perhaps a few hours. The heaviest particulates begin to settle as soon as they enter the receiving waters, and tend to form near-bottom plumes that move offshore into deeper waters. There is also a buildup of visible discharge debris around the outfalls covering an area of up to 0.6 hectares (1.4 acres); there are indications of year-around impacts on the benthic biota within these patches.

During the wet season, typified by frequent discharges and lack of stratification in the receiving waters, the lighter discharge particulates rise to the surface and are ultimately swept away by longshore currents. Much of this material may ultimately leave the lake, passing through the ship canal and into Puget Sound; however, the true fate of these materials is uncertain. Downstream of very large particulate inputs such as rivers or multiple CSOs and SDs, the longshore currents also move thick layers of particulates along the shore at depth; this is probably the principal mechanism responsible for raising the concentration of sediment contaminants in areas such as Control Site 3, which is free of outfalls.

All of the CSOs discharging into Lake Washington are confined to a 28.8 km (18 mi) strip of the western shore. If, for the sake of discussion, the particulate mass discharged annually by CSO 023 (Table 8) is accepted as a representative mean* for the 40 CSOs in the area mentioned, the resultant combined annual discharge would be on the order of 1.3×10^8 g of solids. This is equivalent to 4.5 kg per meter of shoreline per year. For an estimated mean width of 250 m for the adjacent littoral zone, the relative deposition rate of a uniform blanket of the discharged solids would be 18 $g/m^2/yr$ assuming 100% settling. The corresponding rate for deposition of SD solids (based on data for SD 7, Table 8) would be 22 $g/m^2/yr$, for 49 SDs in the same area.

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*In truth, CSO 023 is one of the larger Lake Washington outfalls and the calculations based on this assumption are for relative comparison only. The absolute values derived here for both CSO 023 and SD 7 are overestimates.

Were the discharged particulates in fact retained and evenly distributed throughout the littoral zone, the benthos within each square meter would thus annually be subjected to substantial inputs of solid pollutants and the attendant impacts. However, the distributions of discharge particulates have been found to be very uneven, as summarized previously. The data in Table 12 indicate that the background-subtracted input to the sediments immediately surrounding each outfall is on the order of 0.5 $g/m^2/day$, or 1.9×10^2 $g/m^2/yr$. Within an average-sized area of near-outfall debris (perhaps 0.8 hectares), this rate of deposition would account for more than a third of the total inputs calculated previously for the entire littoral zone. Stated otherwise, perhaps 35% of the particulates discharged by the CSOs and SDs initially settles within about 50 m of the outfalls, a total area representing approximately 10% of the littoral zone.

Accordingly, if advective losses from the lake are also considered, it seems probable that appreciably less than half of the total annual mass of discharged particulates remains to blanket the remainder of the littoral sediments through processes of diffuse spreading. Much of the solid material that initially settles around the outfalls moves offshore soon thereafter in near-bottom plumes that stream into the profundal; resuspension and longshore advection may ultimately redistribute part of the remainder.

Based on these observations and the correlating information presented in Figures 24-26 and Table 15, the prevalent sink for the discharge particulates in the lake seems to be the offshore depths. The CSO- and SD-derived solids that are transported by longshore advection have only a limited tendency to settle in the littoral zone as indicated by the data in Table 15 for Control Site 3. For Lake Washington then, discharge impacts on benthic communities, as measurable by present techniques, are probably confined to the near-outfall areas (representing perhaps 10% of the littoral zone), and to the contiguous portions of the profundal.

Marine Environment

As compared to the physical regime controlling the dispersion of particulates discharged into Lake Washington, there are several significant differences associated with Seattle's marine discharges. These are: fewer, but larger point-source inputs; and more dynamic nearshore circulation. Elliott Bay and the Duwamish River estuary (Figure 1), for example, have a combined total of 30 CSOs for 31 km (19 mi) of shoreline. Six of these structures have a mean annual discharge in excess of 4.0 x 10^4 m^3 (10.5 MG); two (including the Denny Way Regulator outfall), have a mean annual discharge of over 7.6 x 10^5 m^3 (200 MG) (Brown and Caldwell, 1979). The nearshore circulation patterns include strong nearshore tidal currents with localized eddies (Tomlinson et al., 1976), and the often silt-laden plume of the Duwamish River which enters Elliott Bay at a mean rate of 37 m^3 (9.7 x 10^3 gallons) per second.

Relative to the dispersion of discharged particulates, these two characteristics are somewhat counterbalancing. Even though the annual mass discharge from some of the marine outfalls is much greater than for a typical outfall in Lake Washington, the stronger nearshore circulation more effectively disperses the marine discharge plumes. As additional consequences, a smaller fraction of the total particulate input settles near marine outfalls and less material subsequently moves offshore in near-bottom plumes.

However, for a very large outfall such as that at the Denny Way Regulator, the additional input is not fully compensated for by the greater dispersion efficiency. The net result is that the area of measurable biological impact around the Denny Way CSO was found to be only about ten times that at CSO 023 in Lake Washington, even though the measured mass ratio of their annual particulate discharges was 26:1.

Compared to the nearshore waters of Lake Washington, then, Seattle's marine littoral zones are likely less impacted by CSO and SD particulates. The heavily-industrialized Duwamish River estuary may be an exception to this supposition due to potentially more toxic wastes. A few areas (including the Denny Way CSO) may be expected to have biological impacts greater than those determined for outfalls in Lake Washington due to unusually large discharge inputs.

DISTRIBUTION AND EFFECTS OF DISCHARGE-BORNE VIRUSES

As noted in the present study and in past investigations as well (Tomlinson et al., 1976) there are numerous bathing beaches and houseboat communities (where swimmers are also frequently seen) in the Seattle area that are in close proximity to combined sewer outfalls. In many instances, the swimming areas are in the path of prevailing longshore flow that dictates the nearshore dissemination of discharge plumes for the neighboring outfalls. Further, the tendency of some of these systems, such as CSO 023, to overflow with only moderate rainfall could result in the contamination of bathing areas by spring or summer showers that are quickly followed by warm weather and heavy use of the swimming areas. The potential for viral infection of swimmers under such circumstances is apparent, but difficult to quantify, as discussed below.

For several reasons, our estimates of the numbers of viruses in combined sewer discharge are probably very low: First, the virus filtering technique involves adjusting the pH of the sample water from 3.5 to 11.5, and this is detrimental to some types of viruses. Second, the BGM cells used in our assays are not appropriate for the detection of many of the serotypes of viruses present in sewage. They are, however, excellent for the growth of polioviruses and Coxsackieviruses which are prevalent in sewage from this area. Third, the viruses from some 40 of our sewage samples, as identified by a laboratory at the University of Washington, were found to consist of only two types - polioviruses and Coxsackie B viruses (included in those samples were the two raw combined sewer overflow water samples processed for the present study; all of the samples were processed using procedures identical to those used in this study). The polioviruses and Coxsackie B viruses account for less than 9% of the serotypes of viruses known to be excreted in the feces of humans, including the adenoviruses, echoviruses, Coxsackie A viruses, reoviruses, rotaviruses, and hepatitis A viruses. In the Seattle Virus Watch program of 1965-1969 the adenoviruses were the types most frequently isolated from human fecal specimens (Cooney et al., 1972).

It has been shown by several investigators (Clark and Chang, 1959; Joyce and Weiser, 1967; and Metcalf and Stiles, 1967) that viruses can survive for long periods of time in water. The most critical influencing factors appear to be the temperature and organic content of the water (Mitchell and Jannasch, 1969; Prier and Riley, 1967). Survival is inversely proportional to temperature and directly proportional to the organic content. The temperature along Lake Washington beaches rarely exceeds 20°C in the summertime and is generally about 18°C. It is estimated that for the interoviruses (polio-, Coxsackie-, and echoviruses) at about 15°C there occurs only a 2 log reduction in virus titers after 10 days (Metcalf and Stiles, 1967). Clearly, after taking into consideration the absolute number of viruses discharged into the receiving water, the survivability of viruses in water, the organic material discharged by an overflow, the potential drift of the plume toward the beach, and the very low dose required for viral infections (Beard, 1965), one must conclude that combined sewer overflows may present a health hazard to people using Lake Washington beaches after overflows, particularly during the summer months. Further work needs to be done in tracing plumes toward the beaches and in determining the relevant viral dilutions.

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APPENDIX

TABLE A-1. DRY WEIGHT CONCENTRATIONS OF VARIOUS PARAMETERS DETERMINED FOR SURFACE(a) SEDIMENTS COLLECTED AT VARIOUS NEARSHORE LOCATIONS(b) IN LAKE WASHINGTON DURING JANUARY, 1978

STN TYPE	STN NO.	DATE	(c) R	(d) S	AL (PPM)	CU (PPM)	HG (PPM)	PB (PPM)	ZN (PPM)	TOC %	O&G (PPM)	CH (PPB)	TP (PPM)
C	1	780105	1	A	65	12	0.500	77	98	0.15	1		560
C	1	780105	2	A			0.100						
C	1	780105	3	A							120		
C	1	780105	4	A			0.060						
C	1	780105	1	B		33	0.100	64	160	0.19	190	4.95	570
C	1	780105	2	B		17		55	67		140		640
C	2	780105	1	A	55	13	0.060	32	80	0.28	1		330
C	2	780105	2	A							160		
C	2	780105	1	B		14	0.080	30	54	0.67	70	7.43	300
C	2	780105	2	B							240		
C	3	771216	1	A	56	11	0.050	43	51	0.17	310		310
C	3	771216	2	A							30		
C	3	771216	1	B		11	0.050	45	59	0.22	1	3.87	290
C	3	771216	2	B			0.055						
C	3	771216	3	B							30		
C	4	771222	1	A	58	18	0.090	110	65	0.96	250		390
C	4	771222	2	A							50		
C	4	771222	1	B		12	0.050	51	70	0.18	70	5.01	330
C	4	771222	2	B		10		42	44				280
C	4	771222	3	B							1		
C	5	771222	1	A	64	5	0.060	60	55	0.38	240		250
C	5	771222	2	A			0.500						
C	5	771222	3	A							1		
C	5	771222	1	B		12	0.200	61	65	0.43	1	26.64	350
C	5	771222	2	B			0.500						
C	5	771222	3	B							1		
C	8	771222	1	A	61	17	0.200	100	73	0.61	220		350
C	8	771222	2	A			0.180						
C	8	771222	1	B		16	0.050	54	69	0.39	510	18.21	330
C	9	771222	1	A	55	12	0.060	19	42	0.53	70		240
C	9	771222	1	B			0.700			0.27	50	10.87	
C	10	780106	1	A	56	7	0.050	42	54	0.55	130		270
C	10	780106	1	B		9	0.060	29	57	0.37	100	6.71	360
C	12	780105	1	A	64	19	0.063	84	84	1.20	1		450
C	12	780105	2	A			0.072						
C	12	780105	3	A							1		
C	12	780105	1	B		30	0.060	66	150	1.20	250	14.04	370
C	12	780105	2	B							1		
C	13	780105	1	A	66	19	0.060	10	140	1.30	170		280
C	13	780105	2	A			0.500						
C	13	780105	3	A							500		
C	13	780105	4	A									280
C	13	780105	1	B		10	0.070	48	30	1.40	60	10.00	190

(continued)

TABLE A-1 (continued)

STN TYPE	STN NO.	DATE	(c) R	(d) S	AL (PPM)	CU (PPM)	HG (PPM)	PB (PPM)	ZN (PPM)	TOC %	O&G (PPM)	CH (PPB)	TP (PPM)
C	13	780105	2	B			0.500						
C	13	780105	3	B							380		
SD	6	771228	1	A	62	40	0.100	370	134	0.84	1400		160
SD	6	771228	2	A			0.060						
SD	6	771228	1	B		29	0.200	230	120	0.79	790	132.60	360
SD	7	771228	1	A	57	33	0.100	260	130	1.10	2000		400
SD	7	771228	2	A	54	28		220	150				380
SD	7	771228	1	B		51	0.200	380	150	1.70	3500	118.47	370
SD	9	780110	1	A	12	23	0.100	420	150	1.40	1800		330
SD	9	780110	1	B		17	0.100	310	110	1.10	1800	41.46	320
SD	11	780109	1	A	60	26	0.200	46	140	0.76	200		310
SD	11	780109	2	A									290
SD	11	780109	1	B		10	0.100	72	31	0.74	210	18.74	280
SD	13	780109	1	A	62	7	0.100	54	47	0.36	50		210
SD	13	780109	1	B		11	0.100	13	68	0.64	1	5.57	230
SD	14	780106	1	A	63	19	0.100	110	82	1.60	220		500
SD	14	780106	1	B		29	0.300	71	140	1.20	240	18.30	500
SD	16	780110	1	A	8	7	0.200	22	150	0.11	130		150
SD	16	780110	1	B		9	0.200	45	95	0.11	80	7.21	400
SD	17	780109	1	A	70	29	0.100	76	160	0.60	510		380
SD	17	780109	2	A									330
SD	17	780109	1	B		35	0.100	63	150	0.47	600	23.73	550
SD	1703	780109	1	A	68	130	0.200	330	410	2.80	2600		610
SD	1703	780109	1	B		38	0.400	360	180	3.30	3600	455.65	610
SD	19	780109	1	A	58	17	0.200	80	80	0.33	1000		390
SD	19	780109	1	B		21	0.100	82	120	0.38	840	25.65	420
SD	20	780109	1	A	24	30	0.300	56	81	7.80	290		590
SD	20	780109	2	A	68	34		30	70		210		580
SD	20	780109	3	A			0.100						
SD	20	780109	1	B						2.00	220	32.75	440
SD	20	780109	2	B							410		
CSO	20	780111	1	A	56	27	0.100	250	100	0.31			370
CSO	20	780111	1	B		60	0.100	52	92	0.65		28.80	410
CSO	23	771227	1	A	45	2160	0.500	170	1500	0.71	1700		3900
CSO	23	771227	2	A	48	120	0.400	220	720		1700		4900
CSO	23	771227	3	A			0.400						
CSO	23	771227	1	B		54	1.100	170	390	0.40	730	106.75	1500
CSO	23	771227	2	B							980		
CSO	30	780111	1	A	60	34	0.160	390	160	1.50	2500		560
CSO	30	780111	2	A			0.150						
CSO	30	780111	3	A									620
CSO	30	780111	1	B		38	0.100	360	170	1.20	1500	113.67	500
CSO	32	780111	1	A	56	33	0.200	45	240	0.71	350		540
CSO	32	780111	1	B		44	0.300	77	120	0.52	260	32.26	820
CSO	36	780110	1	A	53	10	0.050	43	96	0.20	110		420
CSO	36	780110	2	A			0.500						
CSO	36	780110	1	B		10	0.100	81	400	0.37	190	18.01	360
CSO	44	780110	1	A	58	140	0.400	280	560	0.70	1500		1500
CSO	44	780110	1	B		51	0.200	710	300	0.46	1100	35.73	600
CSO	45	780110	1	A	38	26	0.200	250	120	4.90	2800		490
CSO	45	780110	2	A									530
CSO	45	780110	1	B		48	0.200	300	220	3.90	3600	103.78	1200
CSO	46	780110	1	A	50	8	0.055	10	150	0.20	1		300
CSO	46	780110	2	A			0.050						
CSO	46	780110	1	B			0.100			0.29	50	4.76	
CSO	49	771222	1	A	68	64	0.090	220	180	1.10	720		1200
CSO	49	771222	1	B		47	0.500	250	160	1.80	2100	42.73	820

(a) Surface 3 cm, collected by SCUBA divers.
(b) Reference Figures 2 and 8.
(c) Replicate.
(d) Sample.

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TABLE A-2. MEANS, STANDARD DEVIATIONS AND CORRELATION MATRICES FOR CHEMICAL AND PHYSICAL ANALYSES OF SEGMENTS OF SEDIMENT CORES(a) COLLECTED AT COMBINED SEWER OUTFALL 023, STORM DRAIN 7 AND CONTROL SITE 3

CSO 023, Depth=0-0.5 cm

	$\bar{X}$	S_x	% C	% P	ppm Cu	ppm Zn	ppm Pb	% Al
Wet Wt/ Dry Wt	3.35	1.54	.738** (23)	.688* (23)	.459* (22)	.188 (23)	.454* (23)	.318 (23)
% C	2.87	1.85		.348 (23)	.646** (22)	.238 (23)	.415* (23)	.109 (23)
% P	.101	.072			.384* (22)	.181 (23)	.565** (23)	.531** (23)
ppm Cu	39.2	19.74				.363* (22)	.711** (22)	.360* (22)
ppm Zn	168	79.2					.472* (22)	.063 (22)
ppm Pb	129	71.9						.407* (23)
% Al	5.63	.401						

CSO 023, Depth=7-8 cm

	$\bar{X}$	S_x	% C	% P	ppm Cu	ppm Zn	ppm Pb	% Al
Wet Wt/ Dry Wt	1.45	.246	.942** (22)	.096 (21)	-.060 (20)	.664** (21)	.798** (21)	.482* (21)
% C	.843	.686		.180 (21)	-.052 (20)	.674** (21)	.821** (21)	.436* (21)
% P	.043	.021			-.152 (20)	.276 (21)	.013 (21)	.244 (21)
ppm Cu	40.2	48.3				.098 (20)	.024 (20)	-.318 (20)
ppm Zn	91.5	72.8					.714** (21)	.335 (21)
ppm Pb	50.5	55.2						.304 (21)
% Al	5.56	.575						

(continued)

TABLE A-2 (continued)

SD 7, Depth=0-0.5 cm

	$\bar{X}$	S_x	% C	% P	ppm Cu	ppm Zn	ppm Pb	% Al
Wet Wt/ Dry Wt	2.08	.818	.956** (17)	.859** (17)	.465* (17)	.844** (17)	.850** (17)	.072 (17)
% C	1.09	.804		.827** (17)	.440* (17)	.893** (17)	.920** (17)	.094 (17)
% P	.062	.033			.360 (17)	.828** (17)	.729** (17)	.273 (17)
ppm Cu	46.7	25.7				.246 (17)	.596** (17)	-.130 (17)
ppm Zn	60.9	27.0					.826** (17)	.028 (17)
ppm Pb	89.2	52.8						-.010 (17)
% Al	6.07	.328						

SD 7, Depth=7-8 cm

	$\bar{X}$	S_x	% C	% P	ppm Cu	ppm Zn	ppm Pb	% Al
Wet Wt/ Dry Wt	1.46	.181	.596** (17)	.670** (17)	.266 (17)	.239 (17)	.002 (17)	.554* (17)
% C	0.99	.781		.403 (17)	.134 (17)	.049 (17)	-.134 (17)	.356 (17)
% P	.039	.008			.236 (17)	.715** (17)	.440 (17)	.800** (17)
ppm Cu	41.7	23.7				-.069 (17)	.295 (17)	-.121 (17)
ppm Zn	35.3	26.1					.785** (17)	.726** (17)
ppm Pb	46.2	33.3						.402 (17)
% Al	5.97	.286						

(continued)

TABLE A-2 (continued)

C 3, Depth=0-0.5 cm

	$\bar{X}$	S_x	% C	% P	ppm Cu	ppm Zn	ppm Pb	% Al
Wet Wt/ Dry Wt	2.34	1.30	.951** (16)	.902** (16)	.982** (16)	.684** (16)	.894** (16)	-.028 (16)
% C	1.26	.800		.896** (16)	.951** (16)	.747** (16)	.927** (16)	.046 (16)
% P	.080	.034			.891** (16)	.645** (16)	.865** (16)	-.066 (16)
ppm Cu	19.6	10.4				.728** (16)	.885** (16)	-.006 (16)
ppm Zn	131	31.8					.720** (16)	.135 (16)
ppm Pb	85.6	47.0						.083 (16)
% Al	6.13	.399						

C 3, Depth=7-8 cm

	$\bar{X}$	S_x	% C	% P	ppm Cu	ppm Zn	ppm Pb	% Al
Wet Wt/ Dry Wt	1.27	.074	.831** (13)	-.463 (13)	.406 (13)	-.197 (13)	.477* (13)	.262 (13)
% C	.397	.396		-.397 (13)	.502* (13)	.020 (13)	.368 (13)	.068 (13)
% P	.038	.005			-.020 (13)	-.329 (13)	.028 (13)	-.574* (13)
ppm Cu	7.19	2.76				.293 (13)	.407 (13)	-.093 (13)
ppm Zn	51.2	23.7					-.028 (13)	.418 (13)
ppm Pb	20.7	6.09						.052 (13)
% Al	5.60	.218						

(a) Refer to Figures 24-26 for core locations.
* Correlation significant at $\alpha = .05$.
** Correlation significant at $\alpha = .01$.

GLOSSARY

advection - The process of transport of water, or of an aqueous property, solely by mass motion and most typically by horizontal currents.

aeolian transport - Movement of materials between locations by wind.

analysis of variance - A statistical analysis of a set of observations, which entails a separation of the variance (i.e., the square of the standard deviation) of all of the observations into parts, each of which measures the variability attributable to some specific source, such as variations within or between data subsets. The basic emphasis of the analysis is a comparison of the means of these data subsets.

annelid - A multisegmented worm.

anthropogenic - Of, relating to,or influenced by the impact of man on nature.

autecology - The ecological relations between a plant species and its environment.

bathymetry - A set of depth measurements defining the bottom topography of a body of water.

benthic - Of, pertaining to, or living on the bottom of a body of water.

benthos - Bottom-dwelling forms of aquatic life. Also referred to as bottom fauna.

biomass - The dry weight of living matter, including stored food, present in a species population and expressed in terms of a given area or volume of the habitat.

canonical variable - The form of a mathematical variable that represents a reduction to the simplest terms possible, thus maximizing the difference between any two such elements.

carnivore - A flesh-eating animal.

chironomid larva - A juvenile form of a subtaxon of the insect classification known commonly as true flies, the adults of which possess only two wings and a pair of balancers.

cluster analysis - A technique for analyzing biological data that defines community structure by dividing the organisms into related subpopulations based on a grouping of selected variables.

coefficient of determination - The square of the correlation coefficient. A statistical term that generally describes the fraction of X,Y pairs within a given data set that demonstrates a nonrandom relationship.

combined sewer outfall - A structure that discharges a nontreated mixture of sanitary wastes and storm drainage into a receiving water.

condition index - A number that describes the plumpness of a bivalve mollusc.

control - Observation made on sample which has not been contaminated by wastewater, for comparison with observations made on samples which have or may have been so contaminated.

confidence level - The probability that a quantity lies within given numerical bounds.

copepod - A crustacean commonly included in the Entomostraca; represented by free-living, parasitic, and symbiotic forms.

correlation coefficient - A measurement of the tendency of two random variables X and Y to vary together.

correlation matrix - A table of correlation coefficients calculated for all combinations of two of a given set of random variables.

dendrogram - A tree-like graphical representation of an aquatic bottom community, with the schematic branching representing increasingly distinct characteristics separating groups of taxa.

deposit feeder - An animal that feeds on the detritus that collects on the substratum underlying a body of water.

detection limits - The lowest concentration of a chemical or physical constituent that can be measured reproducibly by a given instrument.

diatom - The common name for a class of algae noted for the symmetry and sculpturing of its siliceous cell walls.

discriminant function - A multivariate technique for studying the extent to which different populations diverge or converge with one another.

diversity - A composite measure of the numbers and kinds of organisms in a community.

dye study - An investigation of water movements using a colored dye to mark and trace the circulation of the parcel of interest.

eddy - A vortex-like motion of a fluid running contrary to the main current.

enhancement - The effect of increasing the numbers or biomass of a community of organisms.

enterovirus - One of the two subgroups of small (18 - 30 nanometers) ether-sensitive, human viruses that lack an envelope and have a genetic endowment characterized by ribonucleic acids.

ephemeral - An annual plant that completes its life cycle in one short moist season.

extrapolation - Estimating a function at a point which is larger than (or smaller than) all the points at which the value of the function is known.

feeding type - A grouping of animals based on a common mode of feeding, such as filtration and ingestion of suspended particulates from the surrounding water.

flux - The amount of some quantity flowing through a given area per unit time.

geometric mean - The n^{th} root of the product of n given quantities, a calculated average for which the influence of extreme values is less than for the arithmetic mean of the same set of values.

grab sample - A sediment aliquot collected by a device lowered from the water surface and triggered to take a bite of the underlying substrate with mechanical jaws.

grain size distribution - A quantitative analysis of the spectrum of particle sizes comprising a sediment sample.

hectare - A unit of area equal to 10000 square meters, or 2,471 acres.

infauna - Aquatic animals which live in the sediment underlying a body of water.

inorganic - Pertaining to or composed of chemical compounds that do not contain carbon as the principal element (excepting carbonates, cyanides, and cyanates), that is, matter other than plant or animal.

intertidal zone - The zone between the high-tide and low-tide marks.

isopleth - A line of equal or constant value of a given quantity with respect to either space or time.

lens - A thin layer of surface water of relatively limited dimensions and having properties distinct from those of the water body beneath.

light transmission - The process in which light travels through a medium (such as water) without being absorbed or scattered.

littoral zone - Of or pertaining to the biogeographic zone between the high- and low-water marks.

macroalgae - Large, conspicuous varieties of algae.

median - The quantity or value of that item which is so positioned in a series, when arranged in order of numerical quantity or value, that there are an equal number of items of greater magnitude and lesser magnitude.

metric ton - A unit of mass equal to 1000 kilograms or to approximately 2204.6 pounds.

mollusc - A member organism of one of the divisions of phyla of the animal kingdom containing clams, mussels, oysters, snails, slugs, octopuses, and squid.

morphology - A branch of biology that deals with the form and structure of animals and plants. Also, the external structure of rocks in relation to the development of erosional forms or topographic features.

nematode - A member organism of a group of segmented worms which have been variously recognized as an order, class, and phylum.

oligochaete - A member organism of a class of the phylum Annelida, which includes worms that exhibit both external and internal segmentation.

organic - Of chemical compounds based on carbon chains or rings and also containing hydrogen with or without oxygen, nitrogen, or other elements.

particle size distribution - See grain size distribution.

patchiness - A term used to describe the spacial variability in terms of numbers or biomass of organisms comprising an aquatic bottom community.

pelecypod - A member organism of a large class of the phylum Mollusca containing the clams, oysters, and other bivalves.

periphyton - Sessile biotal components of a freshwater ecosystem.

pollutant loading - The time-integrated mass of a pollutant.

polychaete - A member organism of the largest class of the phylum Annelida, distinguished by paired, lateral, fleshy appendages on most segments.

profundal - The region occurring below the open water zone and extending to the bottom in lakes deep enough to develop temperature stratification.

r-selected - Organisms that are adapted for having a high growth rate, in terms of numbers or biomass.

recruitment - The settling and attachment of immature aquatic organisms.

regression analysis - Given two dependent random variables, regression functions measure the mean expectation of one relative to the other.

serotype - A serological type of intimately related microorganism, distinguished on the basis of its antigenic composition.

skewness - A measure of assymetry in a statistical density function describing numbers of counts vs. a characteristic expressed on a continuous scale.

sorting - The process by which sedimentary particles similar in size, shape, or specific gravity are selected and separated from associated but dissimilar particles by the agent of transportation.

species richness - A numerical expression of the number of species in a collection.

storm drain - A drain which collects and conducts storm runoff water from rain-incident surfaces and interstitial soil seepage into a combined sewer, or a receiving water.

stratification - The arrangement of a body of water, such as a lake, into two or more horizontal layers of differing characteristics, especially densities.

subtidal zone - The region of the bottom of a tidally influenced body of water below the Mean Low Low Water mark.

suspension feeder - An animal that feeds on small particles suspended in water.

taxa - Classified groups of biological organisms.

transmissometer - An instrument for measuring the extinction coefficient (light transmission) of water.